Non-invasive Electrohysterogram Recording using Flexible Concentric Ring Electrode

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***Abstract*— Non-invasive electrohysterogram (EHG) recording could provide valuable information about uterine dynamics. Bipolar EHG has usually been performed using monopolar disposable electrodes. Recently concentric ring electrodes have been used for EHG recordings so as to acquire more localized electrical activity which may be helpful for deducing uterine contraction efficiency. Nevertheless concentric ring electrodes have commonly been implemented in rigid substrates. Therefore they do not adapt to the body surface curvature which may cause discomfort for patients and a poor contact between electrode and skin. The aim of this paper is to examine the feasibility of picking up EHG signals (BC-EHG) using a new flexible tripolar concentric ring (TCR) electrode placed on the abdominal surface, and to compare it with the conventional bipolar recordings. For this purpose, a total of 7 recording sessions were carried out in 7 pregnant women. Each recording implied simultaneous acquisition of one bipolar EHG signal and of two bipolar concentric EHG (BC-EHG) signals using the flexible TCR electrode. Then a set of temporal and spectral parameters was computed from both bipolar EHG and BC-EHG bursts. Experimental results show no noticeable difference in duration and in dominant frequency in Fast Wave High frequency range. Nonetheless, the low frequency content (0.1-0.2 Hz) of BC-EHG records is smaller than that of bipolar record. These results suggest that the new flexible TCR electrode permits to pick up uterine electrical activity and may provide additional information for deducing uterine efficiency.**

I. Introduction

Uterine activity is monitored during pregnancy and childbirth so as to estimate parturition onset as well as for appraising maternal and fetal wellbeing. Previous studies have shown that abdominal surface electrohysterogram (EHG) recording could be used as an alternative technique for assessing uterine activity non-invasively [1, 2, 3]. This latter is made up of two components: the Fast Wave Low (FWL) and the Fast Wave High (FWH), with dominant frequencies between [0.13-0.26] Hz and [0.36-0.88] Hz respectively [4]. FWL is suggested to be related to the propagation and FWH to the excitability to the uterus electrical activity respectively, although this hypothesis is still unproven.

Conventional or high density arrays of monopolar electrodes are usually employed for non-invasive EHG recordings. By applying linear and nonlinear methods in both time and frequency domain it has been shown that EHG features contain useful information for the prediction of birth, both term and preterm and hence for the improvement of the perinatal accomplishment [3, 5, 6]; being specially promising the estimation of the conduction velocity [7, 8] and the study of propagation patterns related to contractions synchronization [9]. However, the measurement of conduction velocity depends on the relative direction of the contraction's propagation with the electrode arrangement, and its accuracy can also be affected by the poor spatial resolution associated to conventional disc electrodes. In this context, concentric ring electrodes have been used in the literature to improve the spatial resolution of surface biosignal recordings [10, 11] and to reduce physiological interferences [12]. Specifically uterine contractions have been identified in EHG signals picked up by concentric ring electrodes implemented on rigid substrates [12]. However the limited ability of those electrodes to adapt to the curvature of the abdominal surface of pregnant women make difficult to ensure good skin-electrode contact, and also provoke certain degree of discomfort to the patient.

Therefore the objective of the present work has been to develop and test flexible concentric ring electrodes for EHG recording, and to compare temporal and spectral parameters with those of conventional bipolar EHG recordings.

II. Material and Methods

A. TCR electrode design & development

The active electrode developed is made up of two parts: a disposable sensing tripolar concentric ring (TCR) electrode printed on flexible substrate, and a reusable battery powered signal conditioning circuit that filters and preamplifies the biosignals before transmission.

The sensing part consisted of two hook-shaped electrodes and an inner circular-shaped electrode (see Fig. 1) so as to be implemented using a monolayer design (no vias are needed). The external diameter of the outer ring was set to 36 mm which is a compromise between signal amplitude and spatial resolution. Technical and physiological issues for electrode dimension design can be found in a previous work of the present research group [13].

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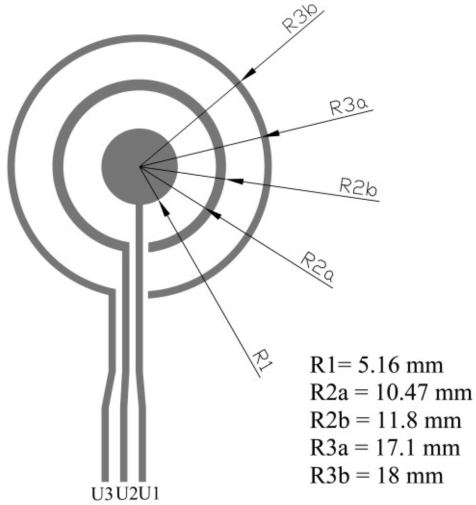

Figure 1: Tripolar concentric electrode for monolayer implementation.

The flexible electrodes were implemented by screen printing technology with a 200 mesh screen. The serigraphy was done by using an AUREL 900 high precision screen stencil printer. Precisely Dupont 5064 silver biocompatible conductor was printed onto polyester film (MelinexST506, Dupont). The curing period of inks was 10 min at 130 ºC.

B. Signal conditioning circuit

For the implemented TCR electrode, it was designed two ultra-high input impedance amplifiers that performed the differential potential between the middle ring and inner disc (U_2-U_1) and between the outer ring and inner disc (U_3-U_1). Each amplifier consisted of a quasi high-pass instrumentation amplifier that provides unity gain for the DC component generated from the half-cell potentials between the skin and electrode, while amplifying the differential potential sensed by TCR electrode [10]. In this work, the preamplifier gain was set to 14.74 being the cut-off frequency of the quasi high pass filter 0.1 Hz. In this way, two bipolar concentric EHG (BC-EHG) recordings can be obtained from each TCR electrode as follows [11]:

$$BC_1 = U_2 - U_1 \tag{1}$$

$$BC_2 = U_3 - U_1 \tag{2}$$

Where U_1, U_2, U_3 are the biopotential picked up by the inner disc, middle ring and outer ring of the TCR electrode respectively.

C. EHG signal acquisition

In this study, 7 pregnant women underwent recording sessions of 30 minutes at Hospital Universitario y Politécnico La Fe de Valencia. All subjects provided written, informed consent. Hospital ethics committee approved the study protocol that adheres to the Declaration of Helsinki. The subjects were healthy women with uneventful singleton pregnancies, and their estimated gestational age ranged from 37 to 41 weeks.

For each recording session, the skin was carefully prepared using an abrasive paste in order to reduce the contact impedance. Two monopolar disposable wet Ag/AgCl electrodes, placed on the uterine median axis and on the middle of the uterus (fundus to symphysis), were used for obtaining monopolar EHG signals, being 25 mm the inter-electrode distance. Two bipolar concentric recordings of EHG were directly obtained using the developed flexible active TCR electrode which was positioned on the uterine median axis and 4 cm above the umbilicus. A thin layer of electrolytic gel was carefully applied to the flexible TCR electrode to ensure good contact between the electrode and skin. Monopolar disposable reference electrodes were placed on each hip of the woman. All recorded EHG signals were band-pass filtered at [0.05, 35] Hz and sampled at 500 Hz.

A tocodynamometer placed on abdominal surface was used to obtain simultaneous non-invasive pressure recordings. This latter was conditioned using the maternal – fetal monitor (Corometrics 170 series, GE Medical systems) and acquired at 4 Hz sampling frequency. All the collected data were displayed in real time and stored digitally for subsequent analysis.

D. Data processing

Since EHG signal distributes its energy mainly from 0.1 to 4 Hz [14], a 5 order Butterworth bandpass digital filter between 0.1 and 4 Hz was used to eliminate undesired components, and then the EHG signal was resampled at 20 Hz. A bipolar EHG signal was obtained from the two monopolar EHG records.

All the EHG bursts were then segmented manually by experts. EHG bursts had to correspond in time to detected contractions on the uterine pressure record, and no artifact evidence must have been observed during contraction. In this work, only the consistent EHG bursts in bipolar EHG and both BC-EHG records were considered for the subsequent analysis, i.e. the differences on the onset and on the offset of the EHG burst among the different channels had to be within ±30s. A total of 21 consistent EHG bursts were detected.

Subsequently, signal characteristics were computed to compare bipolar and BC-EHG records. Although the EHG signal energy is distributed from 0.1 to 4 Hz, many authors suggest analyzing the EHG signal up to 1 Hz in order to reduce cardiac interference influence [2, 15]. In this paper, for bipolar and BC-EHG signals, a set of parameters to characterize the EHG bursts was computed: duration, mean frequency (MF) in the frequency range 0.1-1 Hz, dominant frequency calculated in frequency range 0.1-1 Hz (DF_1) and in 0.34-1 Hz (DF_2) and 3 subband energies normalized respect to the total energy (NE_1: 0.1-0.34 Hz, NE_2: 0.34-1 Hz, NE_3: 1-4 Hz). These parameters have been used in different previous works to characterize EHG bursts [2, 6, 15]. Spectral parameters were obtained from Welch periodograms of signal bursts (4 windows of 60s, overlap adjusted to fit burst duration). These parameters obtained from bipolar and BC-EHG were then compared using paired t-test (α=0.05).

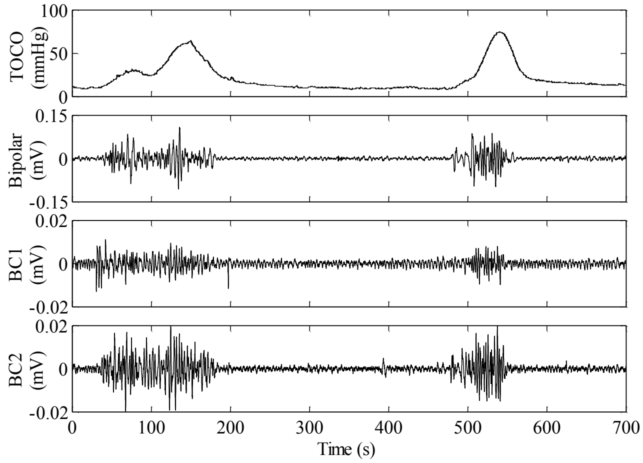

Figure 2: Bipolar and two BC-EHG recordings acquired simultaneously with TOCO in antepartum.

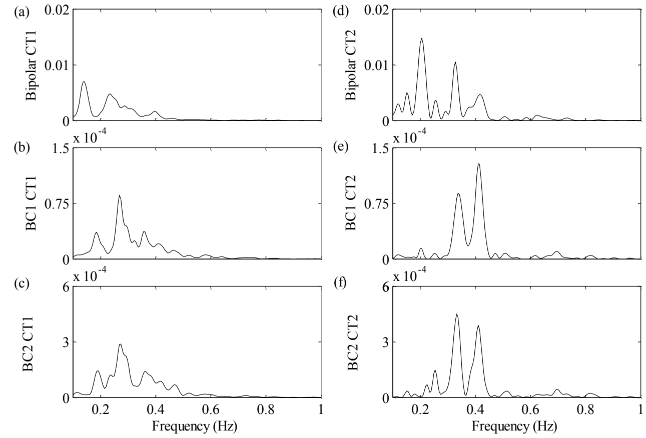

Figure 3: PSD of the EHG bursts shown in Fig. 2. (a)-(c) Contraction extending from 30-178 s. (d)-(f) Contraction extending from 480-550 s.

III. Results

Fig. 2 shows a simultaneous recording of bipolar EHG obtained from two monopolar electrodes and two BC-EHG signals picked up using the flexible TCR electrode. Two contractions can be easily identified in the three channels. Burst in BC-EHG signals are of order of tens of microvolts in amplitude which is smaller than that obtained from the conventional bipolar EHG signal. In addition, the signal amplitude of BC_1 is, in general, smaller than that obtained from BC_2 channel. As for the power spectral distributions (PSDs) of the two EHG bursts, shown in Fig. 3, it can be observed that both BC-EHG contained similar spectral content in FWL and FWH frequency range. In contrast, bipolar EHG burst seems to contain strong low frequency content (from 0.1 to 0.2 Hz), whereas this component seems to have less influence in both BC-EHG signals.

Table I shows the features of the bipolar and the two BC-EHG records for the total number of consistent contractions. Firstly, no statically difference was observed in uterine contraction duration neither in DF_2 (that corresponds to FWH frequency) from bipolar and the two BC-EHG channels. On the other hand, mean frequency, NE_2 and DF_1 obtained from conventional bipolar EHG bursts were significantly smaller than those of BC-EHG bursts. The decrease of NE_2 is related to the increase of NE_1 which is significantly higher in bipolar EHG.

IV. Discussion

In the present work a new flexible TCR electrode has been used for obtaining two BC-EHG recordings, and the signal characteristics were compared with those of simultaneous bipolar EHG recording. To the author's knowledge, this is the first time that these signal characteristics of EHG bursts obtained using concentric ring electrodes are reported. Experimental results showed that uterine electrical activity can be picked up by this kind of electrode since uterine contractile activity was identified and similar signal characteristics were obtained from bipolar EHG and from BC-EHG signals. The different EHG characteristics suggest that the low frequency content in BC-EHG is smaller than that of bipolar EHG recording which is reflected in a decrease of NE_1 (0.64±0.15 vs. 0.76±0.13), thus obtaining higher values of mean frequency, NE_2 and DF_1. This finding may be associated to various factors. Firstly the flexible TCR electrode was connected to a quasi-high pass instrumentation amplifier that permits to reduce the DC component contained in bioelectrical recording. In addition the three poles of the flexible TCR electrode were implemented in the same substrate, which may provide more similar electrode-skin contact potential and a more synchronized and similar response to the abdominal surface stretching during contractions and to movements than that of the two independent monopolar electrodes.

As for the electrode dimensions, the simultaneous recording of BC1 and BC2 allows us to compare the signals obtained in the same location with outer ring diameters of approximately 24 and 36mm, respectively. Firstly no noticeable differences were found in the signal features of the two BC-ECG records, which may be related to the relatively small TCR electrode sensing area. Nonetheless, it has been observed that the EHG bursts of BC2 usually

TABLE I. Mean and standard deviation of the EHG characteristics of bipolar and two BC-EHG records for the total of 21 consistent contractions. * Indicates that statically difference was found in this parameter between Bipolar and each of BC-EHG.

	Duration (s)	**MF (Hz)**	**DF_1**	**DF_2**	**NE_1**	**NE_2**	**NE_3**
Bipolar	92.9±35.2	0.26±0.05	0.19±0.07	0.39±0.03	0.76±0.13	0.22±0.12	0.01±0.014
BC_1	90.8±36.8	0.31±0.05*	0.24±0.08*	0.40±0.06	0.64±0.15*	0.33±0.15*	0.03±0.012*
BC_2	89.3±35.8	0.31±0.05*	0.25±0.10*	0.41±0.05	0.64±0.15*	0.34±0.15*	0.02±0.008*

presented higher amplitude than that of BC1 which may be associated to its greater inter-electrode distance. In comparison with the signal amplitude obtained using tripolar concentric ring electrodes in bipolar configuration (TCB, 36mm outer diameter) reported in previous works [12], that of BC signals recorded in this paper are slightly higher (~30-40 μV for BC-EHG vs ~10μV for TCB); although it should be quantitative evaluated using a more extended database. This finding mainly lies in the fact that, the TCB electrodes used for EHG recording in [12] were dry and implemented onto rigid substrates. In contrast, in the present work it was used a flexible wet TCR electrode which permits a better adaptation to the body curvature and provides better electrode-skin contact potential than rigid substrates, as it was demonstrated on electrocardiographic applications [16]. In this respect, dry electrodes may cause a poor electrode-skin potential contact giving rise to surface recording with low signal-to-noise ratio, high baseline wander and high sensitivity to motion artifacts [12]. This latter may be of special relevance for recording uterine electrical activity since the occurrence of a uterine contraction may also induce movement artifacts due to abdominal deformation, due to forced respiration patterns or due to pain. On the other hand, despite the fact that theoretically concentric ring electrodes in TCB configuration provide higher spatial resolution than bipolar concentric ring electrode [10], a trade-off between spatial resolution and signal amplitude should be achieved. In this sense, the increase in signal amplitude obtained in BC signals from the flexible wet electrode could improve the uterine contraction detectability and the signal-to-noise ratio of non-invasive EHG recording; thereby enhancing the applicability of these electrodes for monitoring uterine activity. From these results it can be confirmed that bipolar concentric ring electrode with an external diameter of 24 mm could be used for high density body surface potential mapping for studying velocity and directionality of the EHG signal propagation.

V. CONCLUSION

Experimental results showed that both BC-EHG records obtained with the new flexible TCR electrode permit to pick up uterine electrical activity. BC-EHG signal, compared to conventional bipolar EHG recording, presents similar spectral characteristics but with smaller low frequency content (between 0.1 and 0.2Hz). Therefore BC-EHG recordings could be used for body surface potential mapping to study the velocity and directionality of the EHG signal propagation; thus obtaining additional information about uterine contraction efficiency.

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REFERENCES

[1] D. Devedeux, C. Marque, S. Mansour, G. Germain, and J. Duchene, "Uterine electromyography: a critical review," *Am. J. Obstet. Gynecol.*, vol. 169, no. 6, pp. 1636-1653, Dec.1993.

[2] W. L. Maner and R. E. Garfield, "Identification of human term and preterm labor using artificial neural networks on uterine electromyography data," *Ann. Biomed. Eng*, vol. 35, no. 3, pp. 465-473, Mar.2007.

[3] R. E. Garfield, W. L. Maner, L. B. Mackay, D. Schlembach, and G. R. Saade, "Comparing uterine electromyography activity of antepartum patients versus term labor patients," *Am. J. Obstet Gynecol*, vol. 193, no. 1, pp. 23-29, July2005.

[4] J. Terrien, C. Marque, and B. Karlsson, "Spectral characterization of human EHG frequency components based on the extraction and reconstruction of the ridges in the scalogram," *Conf. Proc. IEEE Eng Med. Biol. Soc.*, vol. 2007, pp. 1872-1875, 2007.

[5] M. Hassan, J. Terrien, C. Muszynski, A. Alexandersson, C. Marque, and B. Karlsson, "Better pregnancy monitoring using nonlinear correlation analysis of external uterine electromyography," *IEEE Trans. Biomed. Eng*, vol. 60, no. 4, pp. 1160-1166, Apr.2013.

[6] G. Fele-Zorz, G. Kavsek, Z. Novak-Antolic, and F. Jager, "A comparison of various linear and non-linear signal processing techniques to separate uterine EMG records of term and pre-term delivery groups," *Med. Biol. Eng Comput.*, vol. 46, no. 9, pp. 911-922, Sept.2008.

[7] M. Lucovnik, W. L. Maner, L. R. Chambliss, R. Blumrick, J. Balducci, Z. Novak-Antolic, and R. E. Garfield, "Noninvasive uterine electromyography for prediction of preterm delivery," *Am. J. Obstet. Gynecol.*, vol. 204, no. 3, pp. 228-10, Mar.2011.

[8] C. Rabotti, M. Mischi, S. G. Oei, and J. W. Bergmans, "Noninvasive estimation of the electrohysterographic action-potential conduction velocity," *IEEE Trans. Biomed. Eng*, vol. 57, no. 9, pp. 2178-2187, Sept.2010.

[9] T. Y. Euliano, D. Marossero, M. T. Nguyen, N. R. Euliano, J. Principe, and R. K. Edwards, "Spatiotemporal electrohysterography patterns in normal and arrested labor," *Am. J. Obstet. Gynecol.*, vol. 200, no. 1, pp. 54-57, Jan.2009.

[10] C.-C. Lu and P. P. Tarjan, "Pasteless, Active, Concentric Ring Sensors for Directly Obtained Laplacian Cardiac Electrograms," *J. Med. Biol. Eng.*, vol. 22, pp. 199-203, 2002.

[11] W. G. Besio, K. Koka, R. Aakula, and W. Dai, "Tri-polar concentric ring electrode development for laplacian electroencephalography," *IEEE Trans. Biomed. Eng*, vol. 53, no. 5, pp. 926-933, May2006.

[12] J. Alberola-Rubio, G. Prats-Boluda, Y. Ye-Lin, J. Valero, A. Perales, and J. Garcia-Casado, "Comparison of non-invasive electrohysterographic recording techniques for monitoring uterine dynamics," *Med. Eng Phys.*, vol. 35, no. 12, pp. 1736-1743, Dec.2013.

[13] Y. Ye-Lin, E. Senent, G. Prats-Boluda, E. Garcia-Breijo, J. V. Lidon, and J. Garcia-Casado, "Tripolar Flexible Concentric Ring Electrode Printed with Inkjet Technology for ECG Recordings,", *XIII Mediterranean Conference on Medical and Biological Enginerring and Computing* 1 ed Sevilla, Spain: 2013, pp. 1579-1582.

[14] H. Maul, W. L. Maner, G. Olson, G. R. Saade, and R. E. Garfield, "Non-invasive transabdominal uterine electromyography correlates with the strength of intrauterine pressure and is predictive of labor and delivery," *J. Matern. Fetal Neonatal Med.*, vol. 15, no. 5, pp. 297-301, May2004.

[15] D. Schlembach, W. L. Maner, R. E. Garfield, and H. Maul, "Monitoring the progress of pregnancy and labor using electromyography," *Eur. J. Obstet. Gynecol. Reprod. Biol.*, vol. 144 Suppl 1, p. S33-S39, May2009.

[16] G. Prats-Boluda, Y. Ye-Lin, E. Garcia-Breijo, J. Ibañez, and J. Garcia-Casado, "Active flexible concentric ring electrode for non-invasive surface bioelectrical recordings," *Meas. Sci. Technol*, vol. 23, pp. 1-10, 2012.