1. TITLE PAGE

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Feasibility and analysis of bipolar concentric recording of Electrohysterogram with flexible active electrode

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Abbreviated title

Flexible CRE for surface EHG recording

2. Abstract

The conduction velocity and propagation patterns of the Electrohysterogram (EHG) provide fundamental information on the electrophysiological condition of the uterus. However, the accuracy of these measurements can be impaired by both the poor spatial selectivity and sensitivity to the relative direction of the contraction propagation associated with conventional disc electrodes. Concentric ring electrodes could overcome these limitations. The aim of this study was to examine the feasibility of picking up surface EHG signals using a new flexible tripolar concentric ring electrode (TCRE), and to compare these signals with conventional bipolar recordings. Simultaneous recording of conventional bipolar signals and bipolar concentric EHG (BC-EHG) were carried out on 22 pregnant women. Signal bursts were characterized and compared. No significant differences were found between the channels in either duration or dominant frequency in the Fast Wave High frequency range. Nonetheless, the high pass filtering effect of the BC-EHG recordings gave lower frequency content between 0.1-0.2 Hz. Although the BC-EHG signal amplitude was about 5-7 times smaller than that of bipolar recordings, a similar signal-to-noise ratio was obtained. These results suggest that the flexible TCRE is able to pick up uterine electrical activity and could provide additional information for deducing the uterine electrophysiological condition.

Keywords:

Concentric ring electrode, flexible electrode, electrohysterogram

Text

3. Introduction

Preterm births and associated complications are among the most important problems in perinatology, since they represent about 7% of total births and contribute to about 85% of all perinatal deaths.[32] The complications of preterm births include significant neurological, mental, behavioral and pulmonary problems in later life.[32] One of the determining factors of the effectiveness of tocolytic treatments, and therefore of the prolongation of fetal development in the uterus, is the early detection of preterm birth, which depends upon understanding the mechanisms that initiate labor.[28]

Uterine activity is usually monitored during pregnancy and childbirth in order to estimate parturition onset as well as to appraise maternal and fetal wellbeing. Tocography (TOCO), the technique most commonly used at the present time to determine uterine dynamics, consists of detecting changes in the abdominal contour by using external force measurement devices and is an indirect indication of uterine contractions.[28] However TOCO is not a reliable technique, since it mostly depends on the position of the tocodynamometer and on the subjective judgment of the examiner.[22,28] Nor does it provide information on the efficiency and synchronization of uterine contractions, which seem decisive in predicting the delivery time horizon and so in identifying the risk of preterm birth.[12] Despite these drawbacks, TOCO is widely used in maternity clinics due to its non-invasive nature.

Abdominal surface electrohysterogram (EHG) recording has emerged as an alternative technique for assessing uterine activity non-invasively.[4,10,17] The EHG consists of intermittent bursts of spike action potentials which can be initiated in any myometrial muscle cell (pacemaker) and then excite the surrounding cells.[9,11] Uterine electrical activity is low and uncoordinated during early pregnancy, but becomes intense and synchronized as delivery approaches.[4,10] Previous studies have shown that the EHG burst energy is mainly distributed between 0.1-4 Hz[21] and is made up of two components: Fast Wave Low (FWL) and Fast Wave High (FWH), with dominant frequencies between [0.13-0.26] Hz and [0.36-0.88] Hz respectively.[30] It has been suggested that FWL is related to the propagation and FWH to the excitability of uterus electrical activity, respectively, which are the main issues in determining uterine contractility,[4] however this hypothesis still has to be proven. Most EHG studies have focused on changes occurring in the “uterine-dominant” range, i.e. within the 0.34 to 1 Hz frequency range, so as to reduce baseline wander and respiration artifacts, which are typically below 0.34 Hz, and to nullify cardiac components, generally found at above 1 Hz.[10,17]

Conventional or high density arrays of monopolar electrodes are usually employed for non-invasive EHG recordings. Applying linear and nonlinear methods in both time and frequency domains, it has been proven that EHG features could contain relevant information for the prediction of both term and preterm births and so for the improvement of the perinatal accomplishment,[8,10,12] being specially promising for the estimation of conduction velocity[16,25] and the study of propagation patterns related to contraction synchronization[6]. However, estimating the conduction velocity depends on the direction of the contraction propagation in relation to the electrode arrangement,[26] and its accuracy can also be affected by the poor spatial resolution associated with conventional disc electrodes, due to the blurring effect of the volume conductor. In this context, concentric ring electrodes have been proposed in the literature to improve the spatial resolution of surface biosignal recordings[2,14,15] and to reduce different types of physiological interference[23]Theoretical studies of the spatial transfer function of the different configurations of disc and concentric-ring electrodes have also found that higher frequency content and lower amplitudes could be expected from bipolar concentric recordings than from bipolar recording with conventional disc electrodes.[3,7]

Concentric ring electrodes have already been used for EHG monitoring.[1] The configuration of these electrodes permitted the attenuation of cardiac interference in EHG recordings. However, the ring electrodes used were implemented on rigid substrates, which limited their adaptation to the curvature of the abdominal surface of pregnant women, making it difficult to ensure good skin-electrode contact, which was reflected in lower detectability of uterine contraction than in conventional bipolar recordings. Disc electrodes also cause a certain degree of discomfort to the patient. In addition, no differences have been reported between the frequency content of EHG signals recorded from concentric ring electrodes and that of recordings from disc electrodes.

As a necessary next step towards the possible clinical use of concentric ring electrodes, the objective of the present work was therefore to develop and test active flexible ring electrodes for EHG recording, and to compare the temporal and spectral parameters of these signals with those of conventional bipolar EHG recording from disc electrodes. For this purpose, signal bursts were identified and characterized from simultaneous bipolar EHG recordings with conventional disc electrodes and from the proposed concentric ring electrodes (BC-EHG). It was observed that although the BC-EHG bursts presented smaller amplitude, similar results were obtained in parameters such as signal-to-noise ratio, duration and dominant frequency in the Fast Wave High frequency range. The main differences were found in the frequency range from 0.1 to 0.2 Hz due to the high pass filtering effect of concentric ring electrodes. The detectability of uterine contractions was similar in both BC-EHG and bipolar signals, suggesting the feasibility of the proposed flexible ring electrode for the monitoring and analysis of uterine electrical activity.

4. Materials and Methods

A. Concentric Ring Electrode

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

The sensor unit consists of two hook-shaped electrodes and an inner circular electrode (see Fig. 1) so as to be implemented using a monolayer design (no vias are needed). This kind of electrode is able to pick up bioelectric dipoles located at depths approximately equal to the ring diameter.[13] Considering the expected depth of uterine muscle from the abdominal surface, and as a compromise between signal amplitude and spatial resolution, the external diameters of the outer and middle rings were set to 36 mm and 24 mm, respectively. Other technical and physiological issues for electrode dimension design can be found in a previous work by the present research group.[24]

Insert figure 1 here

The flexible electrodes were implemented by screen printing technology with a 200 mesh screen. The serigraphy was performed by an AUREL 900 high-precision screen stencil printer. The ink curing period was 130 ºC for 10 min. A Dupont 5064 silver biocompatible conductor was printed onto polyester film (MelinexST506, Dupont).

B. Signal conditioning circuit

Two ultra-high input impedance amplifiers were designed for the TCRE to perform 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 differential input, quasi high-pass instrumentation amplifier to provide unity gain for the DC component generated from the half-cell potentials between the skin and electrode while amplifying the differential potential sensed by the TCRE.[15] Specifically, a single resistor-capacitor set, connected in series serves as a high-pass filter for both input leads, so as to obtain a preamplifier gain of 14.74, the cut-off frequency being 0.1 Hz. The dual-channel AD8222 (Analog Devices, Norwood, MA, USA) high performance instrumentation amplifier was chosen for its implementation. In this way, two bipolar concentric EHG (BC-EHG) recordings can be obtained from the TCRE as follows:[2]

$$BC_1 = U_2 - U_1 \quad (1)$$

$$BC_2 = U_3 - U_1 \quad (2)$$

Where U_1, U_2, U_3 are the biopotentials picked up by the inner disc, middle ring and outer ring of the TCRE, respectively.

C. EHG signal acquisition

In this study 22 pregnant women underwent 30-minute recording sessions under physiological conditions (no drug was administered) at the *Hospital Universitario y Politécnico La Fe*, in Valencia. All the subjects provided written informed consent forms. The Hospital Ethics Committee approved the study protocol, which adhered to the Declaration of Helsinki. The subjects were healthy women with uneventful singleton pregnancies and their estimated gestational age was between 37 and 41 weeks. The maternal ages were within the 21 to 42 year-old range and the body mass index ranged from 20.8 to 40 kg/m^2.

For each recording session the abdominal skin was carefully prepared using an abrasive paste to reduce skin-electrode contact impedance. Two disposable monopolar Ag/AgCl electrodes (EL501, Biopac Systems Inc, Santa Barbara, CA, USA) were used to obtain one conventional bipolar EHG signal, placed on the uterine median axis at the center of the uterus (fundus to symphysis), the inter-electrode distance being 25 mm. Two bipolar concentric EHG recordings were directly obtained using the developed flexible active TCRE, which was positioned over the uterine median axis 4 cm above the umbilicus. A thin layer of electrolytic gel (Signa Gel, Parker Laboratories, Inc., Fairfield, NJ, USA) was carefully applied to the flexible TCRE to ensure good contact between electrode and skin. This electrode arrangement was due to the fact that in the vertical median line of the abdomen, the distance between the recording site on the skin and the signal source in the myometrium is reduced with respect to the lateral sides.[20] On the other hand, in the region surrounding the umbilicus the position of the uterus relative to the abdominal wall is constant, even during contractions,[4] resulting in a better signal-to-noise ratio. Monopolar disposable reference and ground electrodes were placed on the subjects' hips. All recorded EHG signals were band-pass filtered at [0.05, 35] Hz by Biopac ECG100C commercial biosignal amplifiers (Biopac Systems Inc., USA) and sampled at 500 Hz.

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

D. Data processing

Since EHG signals mainly distribute their energy from 0.1 to 4 Hz,[21] a 5th order Butterworth bandpass digital filter between 0.1 and 4 Hz was used to eliminate undesired components, after which the EHG signal was resampled at 20 Hz.

All the EHG bursts were then segmented manually according to the rules specified below. The EHG bursts had to correspond in time to the contractions detected in the uterine pressure record, and no artifact evidence should 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 among the different channels at the onset and offset of the EHG burst had to be within ±30s.

Subsequently, the signal characteristics of the consistent EHG bursts were computed to compare bipolar and BC-EHG records. For both bipolar and BC-EHG signals, a set of parameters was computed to characterize the EHG bursts used in different previous works:[8,17,28] duration, peak-to-peak amplitude, 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 subband energies normalized with respect to total energy. This latter was defined as follows:

$$NE = \frac{\sum_{f=f_L}^{f_H} PSD_{Burst}[f]}{\sum_{f=0.1Hz}^{4Hz} PSD_{Burst}[f]} \tag{3}$$

Where $PSD_{Burst}[f]$ is the power spectral density using Welch averaged modified periodograms of bipolar and/or BC-EHG signal bursts with a window length of 60s, f_L and f_H are the considered frequency limit to compute the subband energies. The next subband energies were then computed: NE_1: 0.1-0.2 Hz, NE_2: 0.2-0.34 Hz, NE_3: 0.34-0.6 Hz, NE_4: 0.6-1 Hz, NE_5: 1-4 Hz.

The signal-to-noise ratio of the EHG bursts was worked out in order to compare the quality of bipolar and BC-EHG signals. Assuming that the baseline activity did not vary significantly throughout the 30-min recording, the same segment of baseline activity for both bipolar and BC-EHG records was manually identified with the help of TOCO in each recording session. The signal-to-noise ratio was then calculated as the ratio between the power of the EHG bursts and that of baseline activity,[17] calculated using Welch averaged modified periodograms (window length 60s), which has been proposed for estimating the SNR of electromyografic signals.[5]

$$SNR = 10\log_{10}\left(\frac{Power_{Burst}}{Power_{BS}}\right) = 10\log_{10}\left(\frac{\sum_{f=f_L}^{f_H} PSD_{Burst}[f]}{\sum_{f=f_L}^{f_H} PSD_{BS}[f]}\right) \tag{4}$$

Where $PSD_{Burst}[f]$ and $PSD_{BS}[f]$ are the power spectral density of the EHG burst and that of the baseline activity under analysis, respectively, f_L and f_H are the considered frequency limits for the subband SNR analysis, respectively. Specifically, the SNR was analyzed in the next sub-bands of the signal spectrum for bipolar and both BC-EHG records (SNR_1: 0.1-0.2 Hz, SNR_2: 0.2-0.34 Hz, SNR_3: 0.34-0.6 Hz, SNR_4: 0.6-1 Hz, SNR_5: 1-4 Hz, SNR_T: 0.1-4 Hz). Finally, all these parameters obtained from bipolar and BC-EHG signals were statistically compared using the paired t-test (α=0.05).

5. Results

Figure 2 shows a simultaneous recording of the TOCO, the bipolar EHG obtained from two monopolar disc electrodes and two BC-EHG signals picked up using the flexible TCRE. Two contractions can be easily identified in the three EHG channels. The bursts in BC-EHG signals are of the order of tens of microvolts in amplitude, which is smaller than that obtained from the bipolar EHG signal (hundreds of microvolts). In addition, the signal amplitude of BC_1 is, in general, smaller than that obtained from the BC_2 channel. As for the power spectral distributions (PSDs) of the two EHG bursts, shown in Figure 3, it can be observed that both BC-EHGs contained similar spectral content in the FWL and FWH frequency range. In contrast, bipolar EHG bursts seem 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.

Insert figure 2 and figure 3 here

Figure 4 shows another trace of simultaneous recording of the TOCO, bipolar and the two BC-EHG signals in which non-consistent contraction was recorded. Firstly, it can be clearly observed that the contraction around 150s was simultaneously recorded in all TOCO, bipolar and the two BC-EHG signals, with the difference that the EHG burst in the bipolar channel lasted longer than in both BC-EHG channels. Moreover, a second contraction of low intensity extending from 250 to 400 s appeared in the TOCO recording, which was also reflected as an increase of signal amplitude in the bipolar EHG record. In contrast, in both BC-EHG records this latter seems to be two independent bursts clearly differentiated in the time window. Since the onset or offset of the EHG burst differ by more than 30s in the bipolar and BC-EHG channels, it was considered as a non-consistent contraction.

Insert figure 4 here

Table 1 shows the total number of uterine contractions identified in each recording channel. A total of 71 and 78 consistent contractions with bipolar recordings were detected in BC_1 and BC_2-EHG recordings, respectively. Of these, only 69 contractions were consistent in the bipolar and both BC-EHG channels. The features of the bipolar and the two BC-EHG records for the total of consistent contractions are shown in Table 2. Firstly, no statistical difference was observed in uterine contraction duration and DF_2 (corresponding to the FWH frequency) values from the bipolar and the two BC-EHG channels. On the other hand, mean frequency, NE_2, NE_3, NE_4 and DF_1 values obtained from bipolar EHG bursts were significantly smaller than those of the BC-EHG bursts. The decrease of NE_2 and NE_3 is related to the increase of NE_1 which was significantly higher in bipolar EHG. Concerning the signal amplitude, for the bipolar signals it was in the order of hundreds of microvolts, ranging from 90.5 µV to 948 µV, which was significantly higher than that picked up by the flexible TCRE, which varied from 13.1 µV to 153.9 µV.

Insert table 1 and table 2 here

The mean and standard deviation of the SNR in different subbands of the signal spectrum derived from the bipolar and the two BC-EHG records are given in Table 3. In general, for all EHG signals, the SNR value was higher in both the FWL and FWH range (see SNR_2 and SNR_3) and started to decrease above 0.6 Hz, being the lowest value obtained in the frequency range 1 to 4 Hz (see SNR_5). The statistical analysis indicated that no significant difference was found in the SNR values of bipolar and BC_2-EHG channels, except in the SNR_5. In contrast, the SNR_2 and the SNR_3 value derived from the BC_1-EHG channel was significantly lower than that of the bipolar channels; resulting in a smaller SNR in the whole frequency range of the signal (SNR_T: 9.6±3.2 dB bipolar vs. 8.4±3.0 dB BC_1-EHG, being 9.8±3.6 for BC2-EHG).

Insert table 3 here

6. Discussion

Electrohysterography could benefit from the advantages of concentric ring electrodes over conventional disc electrodes, such as enhanced spatial selectivity and independence of the direction of signal propagation. This could be of great importance in the study of propagation patterns and the estimation of conduction velocity. Nonetheless, concentric ring electrodes present a greater high-pass filtering effect than disc electrodes, which could affect the ability to pick up uterine myoelectrical activity, especially the lower frequency components. Our research group has already proved it is possible to identify uterine contractions in EHG recordings with rigid concentric ring electrodes. In the present work it was intended to work towards the possible clinical application of this type of electrode by studying the effects of this concentric ring configuration on temporal and spectral EHG parameters for two different ring dimensions and by enhancing their usability with a new design implemented on a flexible substrate.

Firstly, the BC-EHG signals acquired from the flexible TCRE identified a slightly lower number of the uterine contractions detected by TOCO than those identified in bipolar signals Uterine contraction detectability by flexible wet TCRE is about 83.5% and 88.6% for BC_1 and BC_2 channels, respectively, which is only slightly less than that of bipolar signals (92.7%). This higher detectability of conventional bipolar recordings could be attributed to the electrode location, since it has been reported that the best location for capturing uterine electromyographic activity is over the median axis below the umbilicus,[4,20] where the conventional disc electrodes were placed. Regarding signal amplitude, on average that of BC_1 and BC_2 was 6.5 times and 4.6 times inferior to that obtained in bipolar signals, respectively. These experimental results are consistent with theoretical ones and are probably associated with the smaller inter-pole distance in the TCRE than in bipolar recording by conventional disc electrodes (bipolar: 25 mm; BC_1:5.31 mm; BC_2: 11.94 mm). Despite the differences in signal amplitude, similar signal quality was obtained for bipolar EHG and BC-EHG recordings; with SNR values of: bipolar: 9.6 dB; BC1:8.4 dB; BC2: 9.8 dB, which are slightly higher than the values reported by other authors for EHG recordings with conventional disc electrodes.[1,17,27,31] For both recording techniques, the frequency content over 1 Hz was almost negligible (<3%) and no significant differences in the duration, or DF_2 ,were found, all these values being consistent with those reported by other authors for subjects with similar gestational ages.[10,17-19,29] The main differences were in the signal energy in the low frequency content (from 0.1 to 0.2 Hz) of the signal spectrum. This was significantly smaller in BC-EHG channels than in bipolar EHG recordings, thus obtaining higher values of mean frequency and dominant frequency between 0.1-1 Hz. This finding could be due to various factors: firstly, according to the theory, the BC configuration has a greater high-pass filtering effect than conventional bipolar recording.[3,7] This effect is emphasized when the size of the TCRE is reduced. Secondly, the flexible TCRE was connected to a quasi-high pass instrumentation amplifier that reduced the DC component in bioelectrical recording. Thirdly, the three rings of the flexible TCRE were implemented on the same substrate, which probably provides more similar electrode-skin contact potential and a more synchronized response to abdominal surface stretching during contractions than that of the two independent monopolar electrodes. If this energy reduction at lower frequencies was associated to an attenuation of specific uterine components, the proposed TCRE electrode would not be suitable to study the basal tone or the FWL component of the EHG, which would require the development of larger TCRE electrodes or conventional disc electrodes for monopolar recordings. However it is noteworthy that most of the parameters used to estimate the onset of labor are worked out in the FWH bandwidth.[10,17]

With reference to the dimensions of the proposed electrode, no noticeable differences were found in the features of both BC-EHG records, which may be related to the relatively small TCRE sensing area. Nonetheless, in accordance with the theoretical studies,[3,7] the EHG bursts of BC_2 were seen to present a higher amplitude and better SNR than those of BC_1, which may be associated with the greater inter-electrode distance of BC_2. From these results, despite the attenuation and the high-pass filtering effect, it can be considered that bipolar concentric ring electrodes with an external diameter of 24 mm could be used for high-density body-surface potential mapping for studying velocity and patterns of EHG signal propagation. It should be highlighted that although the higher spatial resolution of concentric ring electrodes over conventional disc electrodes has not been specifically quantified in this work, this enhanced capability to record more localized myoelectrical activity seems to be the reason why in the example shown in Figure 3, two separate signal bursts could be identified in BC-EHG, whereas only one longer one could be observed in the conventional bipolar EHG recording which picks up a more global activity. In fact, the reverse phenomenon, i.e. a uterine contraction that appeared as two independent EHG bursts in the bipolar channel but as a single longer contraction in the BC-EHG channel, was not observed during the entire study.

In comparison to previous studies with rigid concentric ring electrodes (24mm equivalent diameter)[1], the new flexible electrode provided enhanced signals in terms of signal amplitude (flexible:~30,40 µV; rigid: ~10µV), quality (SNR flexible: 8.4 dB, 9.8dB; rigid: 7.6dB) and contraction detectability (flexible: 83.5%, 88%; rigid: ~70%). This enhancement is due to several factors. A flexible substrate adapts better to the body curvature and provides better electrode-skin contact potential than rigid substrates, as has been demonstrated in electrocardiographic applications.[24] Also, unlike the rigid electrode, the new TCRE is used with gel. Dry electrodes may cause poor electrode-skin potential contact, giving rise to surface recording with a low signal-to-noise ratio, high baseline wander and high sensitivity to motion artifacts.[1] This latter effect may be of special relevance when recording uterine electrical activity, since a uterine contraction may also induce movement artifacts from the abdomen, forced respiration patterns or response to pain.

Finally, although the ability of the flexible TCRE to pick up uterine electrical activity has been demonstrated, the present study is not exempt from certain limitations. Firstly, only two BC-EHG records from a relatively small region were obtained using a flexible TCRE, which makes it difficult to estimate the conduction velocity and study propagation patterns in these recordings. Nevertheless, the results of this work make it possible to obtain body surface potential mapping from an array of flexible concentric ring electrodes for the measurement of conduction velocity and to compare it with those obtained from conventional disc electrodes. Secondly the number of patients involved is small and should be increased in future studies. In addition, the disc electrodes that performed the conventional bipolar recordings and the flexible TCRE used to obtain the BC-EHG signals were placed in different locations, which could affect the interpretation of the results to some extent. Also, our study was focused on the last weeks of singleton pregnancies. The results should be compared with recordings at different gestational ages and in obese patients in order to assess the utility of the proposed flexible TCRE to predict labor and assess the preterm birth risk. As the signal amplitude is low during the early stages of pregnancy, the poor signal-to-noise ratio could make recording the BC-EHG still more of a challenge. The development of ultra-low noise bioamplifiers that could acquire biosignals of a few microvolts and the application of more sophisticated signal-processing techniques would make a large contribution to the clinical application of this non-invasive myoelectric technique.

7. Conclusions

The experimental results showed that uterine electrical activity can be picked up by the new flexible wet TCRE, with uterine contraction detectability at about 85%. When compared with bipolar recordings, no significant difference was found for BC-EHG burst duration and dominant frequency in the Fast Wave High Frequency range. However, the signal amplitude was about 5-7 times lower than that of bipolar recordings. It has also been shown that BC-EHG bursts presented similar signal energy distribution to that of bipolar recordings, with the difference that the latter had a smaller low-frequency content (between 0.1 and 0.2Hz). The BC-EHG signal quality sensed by this type of electrode was comparable to that of bipolar ones. Therefore, BC-EHG recordings, which acquire more localized electrical activity, could be used for body surface potential mapping to study the velocity and patterns of EHG signal propagation in order to obtain additional information on uterine contraction efficiency.

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10. Tables

TABLE 1: TOTAL NUMBER OF UTERINE CONTRACTIONS DETECTED IN TOCO, AND THE CORRESPONDING CONSISTENT CONTRACTIONS IN BIPOLAR AND BC-EHG RECORDS.

N_{TOCO}	Nc TOCO-BIP	Nc TOCO-BC1	Nc TOCO-BC2	N_C TOCO-BIP-BC1	N_C TOCO-BIP-BC2	N_C TOCO-BIP-BC1-BC2
97	90	81	86	71	78	69

TABLE 2. MEAN AND STANDARD DEVIATION OF THE EHG CHARACTERISTICS OF BIPOLAR AND TWO BC-EHG RECORDS FOR THE TOTAL OF 69 CONSISTENT CONTRACTIONS. * INDICATES THAT STATISTICAL DIFFERENCE WAS FOUND IN THIS PARAMETER BETWEEN BIPOLAR AND EACH OF BC-EHG (α=0.05).

	Bipolar	BC_1	BC_2
Duration (s)	81.6±29.5	80.4±29.7	80.6±29.6
Amplitude (μV)	192.5±140.5	28.3±22.4*	42.0±21.7*
MF (Hz)	0.25±0.05	0.30±0.06*	0.30±0.06*
DF_1 (Hz)	0.17±0.06	0.22±0.09*	0.24±0.11*
DF2 (Hz)	0.39±0.04	0.40±0.06	0.41±0.06
NE1	0.47±0.19	0.32±0.15*	0.33±0.17*
NE2	0.31±0.13	0.35±0.12*	0.35±0.12*
NE3	0.17±0.12	0.24±0.13*	0.25±0.14*
NE4	0.03±0.02	0.06±0.04*	0.06±0.04*
NE5	0.01±0.01	0.03±0.02*	0.02±0.01*

TABLE 3. Mean and standard deviation of the SNR of bipolar and the two BC-EHG records for the total of 69 consistent contractions. * Indicates that statistical difference was found in this parameter between Bipolar and each of BC-EHG (α=0.05).

	Bipolar	BC_1	BC_2
SNR_T (dB)	9.6±3.2	8.4±3.0*	9.8±3.6
SNR_1 (dB)	8.2±4.0	8.2±3.7	9.7±3.3
SNR_2 (dB)	11.3±4.5	8.7±3.7*	10.4±4.7
SNR_3 (dB)	11.7±4.6	9.6±4.3*	11.5±5.5
SNR_4 (dB)	8.5±4.2	7.9±4.3	9.6±4.6
SNR_5 (dB)	4.5±3.4	5.3±3.5	6.5±3.2*

FIGURE CAPTIONS.

Figure 1. Tripolar concentric electrode for monolayer implementation.

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

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

Figure 4. Bipolar and two BC-EHG recordings acquired simultaneously with TOCO in antepartum.