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1 **1. TITLE PAGE**

2 **Journal:**

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4 **Title of paper**

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

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19 Abbreviated title

20 Flexible CRE for surface EHG recording

21

## 22 **2. Abstract**

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

### 39 **Keywords:**

40 Concentric ring electrode, flexible electrode, electrohysterogram

41

42

## 43 **Text**

### 44 **3. Introduction**

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

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

62 Abdominal surface electrohysterogram (EHG) recording has emerged as an alternative  
63 technique for assessing uterine activity non-invasively.<sup>4,10,17</sup> The EHG consists of intermittent  
64 bursts of spike action potentials which can be initiated in any myometrial muscle cell  
65 (pacemaker) and then excite the surrounding cells.<sup>9,11</sup> Uterine electrical activity is low and  
66 uncoordinated during early pregnancy, but becomes intense and synchronized as delivery

67 approaches.<sup>4,10</sup> Previous studies have shown that the EHG burst energy is mainly distributed  
68 between 0.1-4 Hz<sup>21</sup> and is made up of two components: Fast Wave Low (FWL) and Fast  
69 Wave High (FWH), with dominant frequencies between [0.13-0.26] Hz and [0.36-0.88] Hz  
70 respectively.<sup>30</sup> It has been suggested that FWL is related to the propagation and FWH to the  
71 excitability of uterus electrical activity, respectively, which are the main issues in  
72 determining uterine contractility,<sup>4</sup> however this hypothesis still has to be proven. Most EHG  
73 studies have focused on changes occurring in the “uterine-dominant” range, i.e. within the  
74 0.34 to 1 Hz frequency range, so as to reduce baseline wander and respiration artifacts, which  
75 are typically below 0.34 Hz, and to nullify cardiac components, generally found at above  
76 1 Hz.<sup>10,17</sup>

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

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

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

## 114 **4. Materials and Methods**

### 115 *A. Concentric Ring Electrode*

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

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

128 

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

### 133 *B. Signal conditioning circuit*

134 Two ultra-high input impedance amplifiers were designed for the TCRE to perform the  
135 differential potential between the middle ring and inner disc ( $U_2-U_1$ ) and between the outer  
136 ring and inner disc ( $U_3-U_1$ ). Each amplifier consisted of a differential input, quasi high-pass  
137 instrumentation amplifier to provide unity gain for the DC component generated from the  
138 half-cell potentials between the skin and electrode while amplifying the differential potential

139 sensed by the TCRE.<sup>15</sup> Specifically, a single resistor-capacitor set, connected in series serves  
140 as a high-pass filter for both input leads, so as to obtain a preamplifier gain of 14.74, the cut-  
141 off frequency being 0.1 Hz. The dual-channel AD8222 (Analog Devices, Norwood, MA,  
142 USA) high performance instrumentation amplifier was chosen for its implementation. In this  
143 way, two bipolar concentric EHG (BC-EHG) recordings can be obtained from the TCRE as  
144 follows:<sup>2</sup>

$$145 \quad BC_1 = U_2 - U_1 \quad (1)$$

$$146 \quad BC_2 = U_3 - U_1 \quad (2)$$

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

### 149 *C. EHG signal acquisition*

150 In this study 22 pregnant women underwent 30-minute recording sessions under  
151 physiological conditions (no drug was administered) at the *Hospital Universitario y*  
152 *Politécnico La Fe*, in Valencia. All the subjects provided written informed consent forms.  
153 The Hospital Ethics Committee approved the study protocol, which adhered to the  
154 Declaration of Helsinki. The subjects were healthy women with uneventful singleton  
155 pregnancies and their estimated gestational age was between 37 and 41 weeks. The maternal  
156 ages were within the 21 to 42 year-old range and the body mass index ranged from 20.8 to  
157 40 kg/m<sup>2</sup>.

158 For each recording session the abdominal skin was carefully prepared using an abrasive  
159 paste to reduce skin-electrode contact impedance. Two disposable monopolar Ag/AgCl  
160 electrodes (EL501, Biopac Systems Inc, Santa Barbara, CA, USA) were used to obtain one  
161 conventional bipolar EHG signal, placed on the uterine median axis at the center of the uterus  
162 (fundus to symphysis), the inter-electrode distance being 25 mm. Two bipolar concentric  
163 EHG recordings were directly obtained using the developed flexible active TCRE, which was



164 positioned over the uterine median axis 4 cm above the umbilicus. A thin layer of electrolytic  
165 gel (Signa Gel, Parker Laboratories, Inc., Fairfield, NJ, USA) was carefully applied to the  
166 flexible TCRE to ensure good contact between electrode and skin. This electrode  
167 arrangement was due to the fact that in the vertical median line of the abdomen, the distance  
168 between the recording site on the skin and the signal source in the myometrium is reduced  
169 with respect to the lateral sides.<sup>20</sup> On the other hand, in the region surrounding the umbilicus  
170 the position of the uterus relative to the abdominal wall is constant, even during contractions,<sup>4</sup>  
171 resulting in a better signal-to-noise ratio. Monopolar disposable reference and ground  
172 electrodes were placed on the subjects' hips. All recorded EHG signals were band-pass  
173 filtered at [0.05, 35] Hz by Biopac ECG100C commercial biosignal amplifiers (Biopac  
174 Systems Inc., USA) and sampled at 500 Hz.

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

#### 179 *D. Data processing*

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

183 All the EHG bursts were then segmented manually according to the rules specified below.  
184 The EHG bursts had to correspond in time to the contractions detected in the uterine pressure  
185 record, and no artifact evidence should have been observed during contraction. In this work  
186 only the consistent EHG bursts in bipolar EHG and both BC-EHG records were considered for  
187 the subsequent analysis, i.e. the differences among the different channels at the onset and  
188 offset of the EHG burst had to be within  $\pm 30$ s.

189 Subsequently, the signal characteristics of the consistent EHG bursts were computed to  
 190 compare bipolar and BC-EHG records. For both bipolar and BC-EHG signals, a set of  
 191 parameters was computed to characterize the EHG bursts used in different previous  
 192 works:<sup>8,17,28</sup> duration, peak-to-peak amplitude, mean frequency (MF) in the frequency range  
 193 0.1-1 Hz, dominant frequency calculated in frequency range 0.1-1 Hz (DF<sub>1</sub>) and in 0.34-1 Hz  
 194 (DF<sub>2</sub>) and subband energies normalized with respect to total energy. This latter was defined as  
 195 follows:

$$196 \quad NE = \frac{\sum_{f=f_L}^{f_H} PSD_{Burst}[f]}{\sum_{f=0.1Hz}^{4Hz} PSD_{Burst}[f]} \quad (3)$$

197 Where  $PSD_{Burst}[f]$  is the power spectral density using Welch averaged modified periodograms  
 198 of bipolar and/or BC-EHG signal bursts with a window length of 60s,  $f_L$  and  $f_H$  are the  
 199 considered frequency limit to compute the subband energies. The next subband energies were  
 200 then computed: NE<sub>1</sub>: 0.1-0.2 Hz, NE<sub>2</sub>: 0.2-0.34 Hz, NE<sub>3</sub>: 0.34-0.6 Hz, NE<sub>4</sub>: 0.6-1 Hz, NE<sub>5</sub>:  
 201 1-4 Hz.

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

$$210 \quad SNR = 10 \log_{10} \left( \frac{Power_{Burst}}{Power_{BS}} \right) = 10 \log_{10} \left( \frac{\sum_{f=f_L}^{f_H} PSD_{Burst}[f]}{\sum_{f=f_L}^{f_H} PSD_{BS}[f]} \right) \quad (4)$$

211 Where  $PSD_{Burst}[f]$  and  $PSD_{BS}[f]$  are the power spectral density of the EHG burst and that of  
212 the baseline activity under analysis, respectively,  $f_L$  and  $f_H$  are the considered frequency limits  
213 for the subband SNR analysis, respectively. Specifically, the SNR was analyzed in the next  
214 sub-bands of the signal spectrum for bipolar and both BC-EHG records (SNR<sub>1</sub>: 0.1-0.2 Hz,  
215 SNR<sub>2</sub>: 0.2-0.34 Hz, SNR<sub>3</sub>: 0.34-0.6 Hz, SNR<sub>4</sub>: 0.6-1 Hz, SNR<sub>5</sub>: 1-4 Hz, SNR<sub>T</sub>: 0.1-4 Hz).  
216 Finally, all these parameters obtained from bipolar and BC-EHG signals were statistically  
217 compared using the paired t-test ( $\alpha=0.05$ ).

## 218 **5. Results**

219 Figure 2 shows a simultaneous recording of the TOCO, the bipolar EHG obtained from  
220 two monopolar disc electrodes and two BC-EHG signals picked up using the flexible TCRE.  
221 Two contractions can be easily identified in the three EHG channels. The bursts in BC-EHG  
222 signals are of the order of tens of microvolts in amplitude, which is smaller than that obtained  
223 from the bipolar EHG signal (hundreds of microvolts). In addition, the signal amplitude of  
224 BC<sub>1</sub> is, in general, smaller than that obtained from the BC<sub>2</sub> channel. As for the power spectral  
225 distributions (PSDs) of the two EHG bursts, shown in Figure 3, it can be observed that both  
226 BC-EHGs contained similar spectral content in the FWL and FWH frequency range. In  
227 contrast, bipolar EHG bursts seem to contain strong low frequency content (from 0.1 to 0.2  
228 Hz), whereas this component seems to have less influence in both BC-EHG signals.

229 

230 Figure 4 shows another trace of simultaneous recording of the TOCO, bipolar and the two  
231 BC-EHG signals in which non-consistent contraction was recorded. Firstly, it can be clearly  
232 observed that the contraction around 150s was simultaneously recorded in all TOCO, bipolar  
233 and the two BC-EHG signals, with the difference that the EHG burst in the bipolar channel  
234 lasted longer than in both BC-EHG channels. Moreover, a second contraction of low intensity  
235 extending from 250 to 400 s appeared in the TOCO recording, which was also reflected as an

236 increase of signal amplitude in the bipolar EHG record. In contrast, in both BC-EHG records  
237 this latter seems to be two independent bursts clearly differentiated in the time window. Since  
238 the onset or offset of the EHG burst differ by more than 30s in the bipolar and BC-EHG  
239 channels, it was considered as a non-consistent contraction.

240 Insert figure 4 here

241 Table 1 shows the total number of uterine contractions identified in each recording channel.  
242 A total of 71 and 78 consistent contractions with bipolar recordings were detected in BC<sub>1</sub> and  
243 BC<sub>2</sub>-EHG recordings, respectively. Of these, only 69 contractions were consistent in the  
244 bipolar and both BC-EHG channels. The features of the bipolar and the two BC-EHG records  
245 for the total of consistent contractions are shown in Table 2. Firstly, no statistical difference  
246 was observed in uterine contraction duration and DF<sub>2</sub> (corresponding to the FWH frequency)  
247 values from the bipolar and the two BC-EHG channels. On the other hand, mean frequency,  
248 NE<sub>2</sub>, NE<sub>3</sub>, NE<sub>4</sub> and DF<sub>1</sub> values obtained from bipolar EHG bursts were significantly smaller  
249 than those of the BC-EHG bursts. The decrease of NE<sub>2</sub> and NE<sub>3</sub> is related to the increase of  
250 NE<sub>1</sub> which was significantly higher in bipolar EHG. Concerning the signal amplitude, for the  
251 bipolar signals it was in the order of hundreds of microvolts, ranging from 90.5 μV to 948  
252 μV, which was significantly higher than that picked up by the flexible TCRE, which varied  
253 from 13.1 μV to 153.9 μV.

254 Insert table 1 and table 2 here

255 The mean and standard deviation of the SNR in different subbands of the signal spectrum  
256 derived from the bipolar and the two BC-EHG records are given in Table 3. In general, for all  
257 EHG signals, the SNR value was higher in both the FWL and FWH range (see SNR<sub>2</sub> and  
258 SNR<sub>3</sub>) and started to decrease above 0.6 Hz, being the lowest value obtained in the frequency  
259 range 1 to 4 Hz (see SNR<sub>5</sub>). The statistical analysis indicated that no significant difference  
260 was found in the SNR values of bipolar and BC<sub>2</sub>-EHG channels, except in the SNR<sub>5</sub>. In

261 contrast, the  $SNR_2$  and the  $SNR_3$  value derived from the  $BC_1$ -EHG channel was significantly  
262 lower than that of the bipolar channels; resulting in a smaller SNR in the whole frequency  
263 range of the signal ( $SNR_T$ :  $9.6 \pm 3.2$  dB bipolar vs.  $8.4 \pm 3.0$  dB  $BC_1$ -EHG, being  $9.8 \pm 3.6$  for  
264  $BC_2$ -EHG).

265 Insert table 3 here

## 266 **6. Discussion**

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

279 Firstly, the BC-EHG signals acquired from the flexible TCRE identified a slightly lower  
280 number of the uterine contractions detected by TOCO than those identified in bipolar signals  
281 Uterine contraction detectability by flexible wet TCRE is about 83.5% and 88.6% for  $BC_1$   
282 and  $BC_2$  channels, respectively, which is only slightly less than that of bipolar signals  
283 (92.7%). This higher detectability of conventional bipolar recordings could be attributed to  
284 the electrode location, since it has been reported that the best location for capturing uterine  
285 electromyographic activity is over the median axis below the umbilicus,<sup>4,20</sup> where the

286 conventional disc electrodes were placed. Regarding signal amplitude, on average that of BC<sub>1</sub>  
287 and BC<sub>2</sub> was 6.5 times and 4.6 times inferior to that obtained in bipolar signals, respectively.  
288 These experimental results are consistent with theoretical ones and are probably associated  
289 with the smaller inter-pole distance in the TCRE than in bipolar recording by conventional  
290 disc electrodes (bipolar: 25 mm; BC<sub>1</sub>:5.31 mm; BC<sub>2</sub>: 11.94 mm). Despite the differences in  
291 signal amplitude, similar signal quality was obtained for bipolar EHG and BC-EHG  
292 recordings; with SNR values of: bipolar: 9.6 dB; BC1:8.4 dB; BC2: 9.8 dB, which are  
293 slightly higher than the values reported by other authors for EHG recordings with  
294 conventional disc electrodes.<sup>1,17,27,31</sup> For both recording techniques, the frequency content  
295 over 1 Hz was almost negligible (<3%) and no significant differences in the duration, or DF<sub>2</sub>  
296 ,were found, all these values being consistent with those reported by other authors for  
297 subjects with similar gestational ages.<sup>10,17-19,29</sup> The main differences were in the signal energy  
298 in the low frequency content (from 0.1 to 0.2 Hz) of the signal spectrum. This was  
299 significantly smaller in BC-EHG channels than in bipolar EHG recordings, thus obtaining  
300 higher values of mean frequency and dominant frequency between 0.1-1 Hz. This finding  
301 could be due to various factors: firstly, according to the theory, the BC configuration has a  
302 greater high-pass filtering effect than conventional bipolar recording.<sup>3,7</sup> This effect is  
303 emphasized when the size of the TCRE is reduced. Secondly, the flexible TCRE was  
304 connected to a quasi-high pass instrumentation amplifier that reduced the DC component in  
305 bioelectrical recording. Thirdly, the three rings of the flexible TCRE were implemented on  
306 the same substrate, which probably provides more similar electrode-skin contact potential and  
307 a more synchronized response to abdominal surface stretching during contractions than that  
308 of the two independent monopolar electrodes. If this energy reduction at lower frequencies  
309 was associated to an attenuation of specific uterine components, the proposed TCRE  
310 electrode would not be suitable to study the basal tone or the FWL component of the EHG,

311 which would require the development of larger TCRE electrodes or conventional disc  
312 electrodes for monopolar recordings. However it is noteworthy that most of the parameters  
313 used to estimate the onset of labor are worked out in the FWH bandwidth.<sup>10,17</sup>

314 With reference to the dimensions of the proposed electrode, no noticeable differences were  
315 found in the features of both BC-EHG records, which may be related to the relatively small  
316 TCRE sensing area. Nonetheless, in accordance with the theoretical studies,<sup>3,7</sup> the EHG  
317 bursts of BC<sub>2</sub> were seen to present a higher amplitude and better SNR than those of BC<sub>1</sub>,  
318 which may be associated with the greater inter-electrode distance of BC<sub>2</sub>. From these results,  
319 despite the attenuation and the high-pass filtering effect, it can be considered that bipolar  
320 concentric ring electrodes with an external diameter of 24 mm could be used for high-density  
321 body-surface potential mapping for studying velocity and patterns of EHG signal  
322 propagation. It should be highlighted that although the higher spatial resolution of concentric  
323 ring electrodes over conventional disc electrodes has not been specifically quantified in this  
324 work, this enhanced capability to record more localized myoelectrical activity seems to be the  
325 reason why in the example shown in Figure 3, two separate signal bursts could be identified  
326 in BC-EHG, whereas only one longer one could be observed in the conventional bipolar EHG  
327 recording which picks up a more global activity. In fact, the reverse phenomenon, i.e. a  
328 uterine contraction that appeared as two independent EHG bursts in the bipolar channel but as  
329 a single longer contraction in the BC-EHG channel, was not observed during the entire study.

330 In comparison to previous studies with rigid concentric ring electrodes (24mm equivalent  
331 diameter)<sup>1</sup>, the new flexible electrode provided enhanced signals in terms of signal amplitude  
332 (flexible: ~30,40  $\mu$ V; rigid: ~10 $\mu$ V), quality (SNR flexible: 8.4 dB, 9.8dB; rigid: 7.6dB) and  
333 contraction detectability (flexible: 83.5%, 88%; rigid: ~70%). This enhancement is due to  
334 several factors. A flexible substrate adapts better to the body curvature and provides better  
335 electrode-skin contact potential than rigid substrates, as has been demonstrated in

336 electrocardiographic applications.<sup>24</sup> Also, unlike the rigid electrode, the new TCRE is used  
337 with gel. Dry electrodes may cause poor electrode-skin potential contact, giving rise to  
338 surface recording with a low signal-to-noise ratio, high baseline wander and high sensitivity  
339 to motion artifacts.<sup>1</sup> This latter effect may be of special relevance when recording uterine  
340 electrical activity, since a uterine contraction may also induce movement artifacts from the  
341 abdomen, forced respiration patterns or response to pain.

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



## 361 **7. Conclusions**

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

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378 Healthcare.

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468

469 **10. Tables**

470 **TABLE 1: TOTAL NUMBER OF UTERINE CONTRACTIONS DETECTED IN TOCO, AND THE**

471 **CORRESPONDING CONSISTENT CONTRACTIONS IN BIPOLAR AND BC-EHG RECORDS.**

	Nc	Nc	Nc	N <sub>C</sub>	N <sub>C</sub>	N <sub>C</sub>
N <sub>TOCO</sub>	TOCO- BIP	TOCO- BC1	TOCO- BC2	TOCO-BIP- BC1	TOCO-BIP- BC2	TOCO-BIP-BC1- BC2
97	90	81	86	71	78	69

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

	Bipolar	BC <sub>1</sub>	BC <sub>2</sub>
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 <sub>1</sub> (Hz)	0.17±0.06	0.22±0.09*	0.24±0.11*
DF <sub>2</sub> (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*

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484 TABLE 3. MEAN AND STANDARD DEVIATION OF THE SNR OF BIPOLAR AND THE TWO BC-EHG  
485 RECORDS FOR THE TOTAL OF 69 CONSISTENT CONTRACTIONS. \* INDICATES THAT STATISTICAL  
486 DIFFERENCE WAS FOUND IN THIS PARAMETER BETWEEN BIPOLAR AND EACH OF BC-EHG  
487 ( $\alpha=0.05$ ).

488

	Bipolar	BC <sub>1</sub>	BC <sub>2</sub>
SNR <sub>T</sub> (dB)	9.6±3.2	8.4±3.0*	9.8±3.6
SNR <sub>1</sub> (dB)	8.2±4.0	8.2±3.7	9.7±3.3
SNR <sub>2</sub> (dB)	11.3±4.5	8.7±3.7*	10.4±4.7
SNR <sub>3</sub> (dB)	11.7±4.6	9.6±4.3*	11.5±5.5
SNR <sub>4</sub> (dB)	8.5±4.2	7.9±4.3	9.6±4.6
SNR <sub>5</sub> (dB)	4.5±3.4	5.3±3.5	6.5±3.2*

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490

491 **FIGURE CAPTIONS.**

492 **Figure 1.** Tripolar concentric electrode for monolayer implementation.

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

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

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

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