TITLE PAGE

Title of paper (Med. Eng. and Phys):

Comparison of non-invasive electrohysterographic recording techniques for monitoring uterine dynamics

Authors and addresses:

J. Alberola-Rubio[1], G. Prats-Boluda[1], Y. Ye-Lin[1], J. Valero[2], A. Perales[2] and J. Garcia-Casado[1]

1. Instituto de Investigación e Innovación en Bioingeniería. Universidad Politécnica de Valencia; Camino de Vera s/n Ed.8B, 46022 Valencia, Spain.

2. Servicio de Obstetricia y Ginecología. Hospital Universitario y Politécnico La Fe de Valencia; Bulevar Sur SN, 46033, Valencia, Spain

Contact:

Phone:+34 963877007ext. 76027 Fax: +34 963877609

Email: jgarciac@gbio.i3bh.es

Short title: EHG techniques to monitor uterine dynamics

Keywords: Electrohysterogram, uterine electrical activity, uterine electromyogram, Laplacian potential, ring electrodes

Abstract (200 words):

Non-invasive recording of uterine myoelectric activity (electrohysterogram, EHG) could provide an alternative to monitoring uterine dynamics by systems based on tocodynamometers (TOCO). Laplacian recording of bioelectric signals has been shown to give better spatial resolution and less interference than mono- and bipolar surface recordings. The aim of this work was to study the signal quality obtained from monopolar, bipolar and Laplacian techniques in EHG recordings, as well as to assess their ability to detect uterine contractions. Twenty-two recording sessions were carried out on singleton pregnant women during the active phase of labour. In each session the following simultaneous recordings were obtained: internal uterine pressure (IUP), external tension of abdominal wall (TOCO) and EHG signals (5 monopolar and 4 bipolar recordings, 1 discrete approximation to the Laplacian of the potential and 2 estimates of the Laplacian from two active annular electrodes). The results obtained show that EHG is able to detect a higher number of uterine contractions than TOCO. Laplacian recordings give improved signal quality over monopolar and bipolar techniques, reduce maternal cardiac interference and improve the signal-to-noise ratio. The optimal position for recording EHG was found to be the uterine median axis and the lower centre-right umbilical zone.

1 Introduction

Uterine activity is monitored during pregnancy and childbirth to obtain information on uterine contractions to assist in estimating the start and the progress of labour and to assess the state of health of both mother and child. It can also play a vitally important role in diagnosing cases of distocia due to defective, inefficient or inappropriate uterine activity [1-3]. Measuring intrauterine pressure (IUP) is the present *gold standard* in uterine dynamics. Since it indicates the overall pressure in the uterine cavity [4], it has been shown to give reliable information on all the parameters associated with uterine dynamics. However, its application is limited, since placing the pressure catheter in the uterine cavity requires rupturing membranes, which means it cannot be used during pregnancy but only during the final stages of labour. It also tends to increase the incidence of intrapartum infection and there have even been cases of perforation of the uterus and placental abruption [5]. Tocography is the technique most often used at the present time to determine uterine dynamics. Tocodynamometers (TOCO) are external force measurement devices that detect changes in abdominal contour, which is as an indirect indication of uterine contraction [4]. This method does not provide highly reliable information as it depends to a large extent on the subjective judgment of the examiner [4,6,7]. This is due to the fact that it records variations in local pressures and not, as in IUP, the overall pressure, thus making it highly dependent on the position of the tocodynamometer. It is also influenced by the movements of the fetus within the intrauterine cavity, by maternal parameters (such as the fat tissue or the body mass index, BMI), artifacts (respiratory or maternal movements) and by the elastic strap tension used to fasten the tocodynamometer. Therefore, the TOCO must be constantly recalibrated and re-positioned to work correctly [8].

Another technique for monitoring uterine dynamics consists of measuring the myoelectric activity of the uterus on the abdominal surface, known as the *electrohysterogram* (EHG). Previous studies have established that EHG can be recorded on the abdominal surface and that it is temporally related to the contractions of the uterus [9,10]. The EHG consists of intermittent burst of spike action-potentials; single spikes can initiate contractions, but multiple, higher-frequency, coordinated spikes are needed for forceful and maintained contractions [11]. Electrical activity in the myometrium is low and uncoordinated during the early stages of pregnancy, but intense and synchronized as delivery approaches [12].

Conventional mono- and bipolar recordings have certain disadvantages; bipolar and especially monopolar EHG recordings capture interference from other physiological signals, including: abdominal muscle electrical activity, the electrocardiogram, respiratory movements, electrode-skin contact potential fluctuation, and movement artefacts from both mother and fetus. Both mono- and bipolar recordings have also been shown to have low spatial resolution when localizing and differentiating multiple dipole sources, due to the blurring effect of the different conductivities of the volume conductor [13], which can limit their use in signal propagation studies which seems to contain relevant information on the delivery-time horizon [14, 15].

Laplacian potential recordings have thus been proposed to improve the spatial resolution of surface biosignal recordings [16,17]. The Laplacian is the second spatial derivative of the potential picked up on the body surface and enhances the electrical activity near the observation point, reducing the smoothing effects of the volume conductor and providing further information on the location and differentiation of the multiple sources of the current dipoles [17,18]. The Laplacian of a bioelectric potential can be estimated by measurements on the surface by monopolar electrodes and then applying discretization techniques, such as five-point finite difference algorithm or spline surface Laplacian estimator functions [16,18-20], (discrete Laplacian). The Laplacian of the surface potential can also be estimated directly by specially designed concentric annular electrodes. These electrodes have been used to estimate the Laplacian of bioelectric signal potentials such as the ECG [21,22]and the intestinal myoelectrical activity, the electroenterogram (EEnG) [23]. The use of these techniques to EHG recordings, which have similar characteristics to those of intestinal signals, could significantly improve the quality of EHG recordings as compared to conventional mono- and bipolar recordings and contribute to broadening the scope of EHG clinical applications.

The aim of this study is thus to compare the TOCO and EHG recording techniques with IUP in terms of detecting contractions as well as analyzing different EHG recording techniques (monopolar, bipolar, and Laplacian estimation by discretization and by specially designed active annular electrodes) in order to identify the one that provides the best signal quality and best able to detect uterine contractions. The study also includes an analysis of the optimum location for the electrodes to acquire EHG on the body surface.

2. Materials and methods

2.1 Data Recording

Twenty-two recording sessions were performed on women hospitalized for spontaneous or induced labour at the *Hospital Universitario y Politécnico La Fe* in Valencia (Spain) The study adheres to the Declaration of Helsinki and was approved by the Institutional Review Board. The criteria for inclusion in the study were: women in a good state of health, in the first stage of labour of a singleton pregnancy and estimated gestation time between 37 and 41 weeks. Table 1 gives details of the demographic and clinical characteristics of the participants. All the volunteers were informed of the nature of the study, briefed on the recording protocol and signed the consent form. The recording sessions lasted between 30 minutes and 3 hours, depending on the time of the start of the second stage of labour and the requirements of clinical staff.

Before each recording session the subjects' abdominal area was thoroughly treated with clinical exfoliating cream in order to reduce skin-electrode contact impedance. Five monopolar EHG recordings were obtained from five monopolar 8 mm in diameter Ag/AgCl cup wet electrodes, which correspond to M1-M5 in figure 1. They were arranged in the shape of a cross over the subumbilical uterine median axis, with an inter-electrode distance of 25 mm, as can be seen in figure 1. This electrode configuration also allows to estimate the Laplacian of the potential in the central electrode, according to Hjorth's five-point technique [16]. In addition, two 37 mm external diameter active dry annular electrodes, named L1 and L2, were placed to the left and right of the supraumbilical uterine median axis as shown in figure 1. These active electrodes consisted of 3 conductors (1 inner disk and 2 concentric rings) connected in bipolar configuration (short-circuited internal disk and external ring) that incorporated a signal preconditioning circuit, powered by onboard batteries embedded in the sensor itself that permit to obtain a direct estimation of the Laplacian potential of the EHG.[24]. The characteristics of these electrodes have been described in previous studies [23]. A silicone matrix was developed to hold and put the electrodes in position (see figure 1). Two 8 mm Ag/AgCl cup electrodes were also placed on each of the subjects' thighs as reference and ground similar to [25]. All EHG signals were amplified and filtered between [0.05, 35] Hz by commercial biosignal amplifiers Biopac ECG100C (Biopac Systems Inc, USA) and acquired at a sampling frequency of 500 Hz. Simultaneously with the EHG signals, intrauterine pressure, tocographic signal and maternal ECG (mECG) were monitored and recorded. IUP was recorded by an ACCU-Trace (Accutrace, Inc., USA) intrauterine pressure catheter connected to a Corometrics 170 Series maternal (GE Healthcare, General Electric Company, USA) fetal monitor. The tocographic signal was recorded by tocodynamometer placed on the abdominal surface connected to a Corometrics 250cx Series monitor (GE Healthcare, General Electric Company, USA). Both mechanical activity signals were acquired at a sampling frequency of 4 Hz. Maternal ECG was recorded to study its influence in EHG recordings. It was acquired in reduced Lead I by using disposable electrodes. This signal was amplified and filtered between [0.05, 35] Hz by Biopac ECG100C (Biopac Systems Inc, USA) and acquired at a sampling frequency of 500 Hz.

In order to obtain simultaneous synchronized EHG, mECG, tocographic and IUP signals, an acquisition program was developed on LabView® (National Instruments Corporation, USA). All the data recorded were shown onscreen in real time and digitally stored for further analysis.

2.2 Data analysis

2.2.1 Obtaining bipolar recordings and EHG discrete Laplacian

The four bipolar EHG and discrete Laplacian signals are calculated digitally from the five monopolar recordings as follows:

$$B_1 = M_1 - M_5;\ B_2 = M_5 - M_3;\ B_3 = M_4 - M_5;\ B_4 = M_5 - M_2 \quad (1)$$

$$L_D \approx \frac{4}{b^2} \cdot \left\{ V_5 - \frac{1}{4}\left(M_1 + M_2 + M_3 + M_4\right) \right\} \quad (2)$$

Where M_i is the potential acquired by electrode i, when i =1..5. B_j is the measured bipolar recording of the EHG signal, when j =1...4 and b is the inter-electrode distance (25 mm). L_D is the estimated discrete Laplacian in accordance with Hjorth's five-point technique [16]. In this work we preferred to work out L_D amplitude in mV so as to compare it to that of conventional bipolar ECG recordings and ringed electrodes. Therefore equation (2) has been calculated without multiplying by $4/b^2$.

2.2.2 Identifying uterine contractions

The uterine contractions present in the different recordings (TOCO, IUP, EHG) were identified by three experts with appropriate electrophysiological training to perform the task, working independently of each other and using the following criteria:

- Significant rise in signal amplitude with respect to the basal period.
- Duration longer than 30 seconds.
- Signal morphology typical of electrophysiological changes. Signals with over-abrupt changes, saturation, or coincidental in time with movements of the patient during the recording session are discarded.

At least two of the three experts had to classify the signal as a contraction for it to be considered valid.

2.2.3 Consistency contraction index

In order to assess the temporal correlation between the contractions detected by IUP (gold standard) as compared to the other techniques (EHG and TOCO), the contraction consistency index used (CCI) by Jezewski and Euliano [8, 26,27] was calculated:

$$CCI = \frac{N_C}{\frac{1}{2}\left(N_T + N_E\right)} \quad (3)$$

Where N_T is the number of contractions detected by IUP. N_E is the number of contractions detected by the channel under study, i.e. monopolar, bipolar, discrete Laplacian, active annular EHG electrodes, and the TOCO. N_C is the number of consistent contractions. A contraction was considered consistent when the distance between the maximum peak of the contraction in the channel under study and the same contraction detected by IUP were within ± 10 seconds of each other. To determine the maximum peak in the EHG signal, the TOCO-like signal was generated using the unnormalized first statistical moment of the Time Frequency representation (spectrogram) in a selected frequency band [0.3 - 0.8] Hz [25].

2.2.4 Quality parameters of the EHG signals

EHG signals are contaminated by other biological signals. The most commonly encountered interferences are caused by: the maternal and fetal electrocardiogram, electrical activity of the abdominal muscle, maternal breathing movements, contact interference, and maternal and fetal movement artefacts. Various estimators have been defined to evaluate the quality of the signals obtained in the presence of interference from these sources.

Interference from maternal ECG

In order to quantify the maternal ECG interference present in the EHG recordings, ,for each of the surface channels (termed as x(t)) ten 60-second baseline sections are extracted and the mECG R-wave is detected by the algorithm proposed by Hamilton & Tompkins (1986) [28]. The average beat $\overline{ECG}$ of mECG interference present in the surface signals is then computed, considering a window from 275 ms before to 450 ms after each R wave detected in the mECG recording and subsequently taking the average of all the windows of the identified beats. An estimate of the mECG interference signal ($I_{mECG}(t)$) present in this interval is then made by assigning the average beat, with the window size indicated above, to each R wave detection instant and giving 0 value outside the window. At this point, the $\overline{EHG(t)}$ signal is estimated by subtracting the estimated mECG interference signal $I_{mECG}(t)$ from the surface signal x(t). The signal-to-mECG interference (S/I_{mECG}) is thus calculated as:

$$S / I_{mECG} = 10 \log \left(\frac{Power\left(\overline{EHG}\right)}{Power(I_{mECG})} \right) dB \quad (4)$$

Power($\overline{EHG}$*)* being the power content of the signal under study and *Power(*I_{mECG}*)* being the power content of the mECG interference signal.

Signal-to-noise ratio

In order to assess the quality of the EHG signal in the contractile period, the signal is filtered in the bandwidth of interest [0.1, 4] Hz and decimated at 20 Hz. The signal-to-noise ratio (S/N), that values the increase on the signal power during contraction with respect to the basal state, is then computed by a method similar to that used by other authors [29-31] :

$$S/N = 10\log\left(\frac{Power(CT) - Power(Basal)}{Power(Basal)}\right) dB \quad (5)$$

Power(CT) being the power content of the EHG signal during the contraction and *Power(Basal)* the power content of the baseline near the contraction. An algorithm was designed for this that selected the nearest non-artefacted 30-second baseline section before and after the contraction analysed.

3. Results

3.1 Consistency of contractions

Figure 2 shows an example of EHG signals (bipolar, monopolar, discrete Laplacian and Laplacian estimated by active annular electrode) recorded simultaneously with intrauterine pressure (IUP) and abdominal distension (TOCO) during a period of contractile activity. It can be seen that a uterine contraction is associated with increased pressure in the IUP and TOCO recordings and with a spike burst containing a rise in amplitude and frequency in the bioelectric signal in the different EHG recordings. The amplitude of the monopolar, bipolar and discrete Laplacian signals is in the order of hundreds of microvolts, and that of the signals captured by the active annular electrode are around 20 times lower.

The total number of contractions identified by each technique and the value of the CCI index that assessed the consistency of the contractions detected by TOCO and EHG in comparison with IUP are given in table 2. IUP detected a total of 479 contractions, while only 289 were detected by the tocodynamometer. All EHG channels present higher consistency values than TOCO. In addition, except for L1 and L2, this difference is significant (ANOVA, p=0.05) if CCI values are analysed for each of the 22 recording sessions (individual values are not given for reasons of space). Monopolar and bipolar EHG signals considerably improve on the consistency indices obtained by TOCO, with values between 88% and 94%. In the set of EHG signals, the B1 recording channel has the best detected CCI. In the monopolar EHG recordings, the best results were given by those supplied by the electrodes placed over the median uterine axis (M1, M3 and M5). As for Laplacian EHG recordings, discrete Laplacian L_D presents a CCI value of 89.3%, similar to that of monopolar and bipolar EHG recordings meanwhile the signals captured by the active annular electrodes show lower contraction consistency index values than the other channels, the CCI value associated with the L1 recording (82.76%) being better than that of the L2 recording (75.39%).

3.2 Resting ECG interference

Figure 3 shows an example of the simultaneous recording of signals captured on the abdominal surface during a period without uterine contractions. Strong interference from maternal cardiac activity can be observed under these conditions in the monopolar recording, which is attenuated in the bipolar recording, while it is not apparent in the Laplacian recordings.

The diagram in figure 4 gives details, in terms of electrode arrangements and recording techniques, of the signal-to-mECG interference ratios. The results are a reflection of the behaviour shown in figure 3. The monopolar recordings are strongly affected by mECG interference, with the M2 recordings on the patient's left-hand side giving the worst results (3.4 ± 7.1 dB). The best are given by the M4 recording (on the right-hand side) at 8.7 ± 7.6 dB. Maternal ECG interference is significantly lower in bipolar than monopolar recordings, although it can be easily identified, with the B1 recording being the most affected (14.5 ± 3.9 dB), and B3, on the patient's right-hand side, the least (20.5 ± 6.4 dB). Laplacian recordings obtained the highest values of this parameter (discrete Laplacian 21.2 ± 4.1 dB, L125.9 ± 5.1 dB and L2 26.9 ± 4.8 dB).

3.3 Signal-to-noise ratio

Figure 5 presents the values of the signal-to-noise ratio obtained during the contractile period according to location and the technique employed to obtain the EHG recordings. It can be seen that the ratios obtained are low, with mean values between 5.1 and 7.6 dB. In general the monopolar recordings have the lowest values, followed by the bipolar and Laplacian. It can also be seen that the channels on the patient's right-hand side present signal-to-noise ratios slightly higher than those on the left. However, all the values show wide variations, both between contractions on the same channel and session and among subjects, as discussed below.

4. Discussion

4.1 EHG vs TOCO for detecting uterine contractions

Researchers in the field of obstetrics are aware of the limitations of the tocodynamometer-based methods of monitoring uterine dynamics at present in use. These devices have comparatively low sensitivity, which can affect the accuracy of contraction amplitude and duration, and it restricts their use in obese parturients. They may even fail to detect contractions altogether due to misalignments of the toco probe caused by maternal movements [3,4,7,27]. In addition, the toco probe needs to be held tight by a strap that applies pressure on the mother's abdomen, which can be uncomfortable and may even be the cause of the appearance of uterine contractions. Many studies point out that EHG recordings could make a large contribution to solving this problem [8,25,27,32]. In fact, previous studies carried out by other research groups have found that monopolar or bipolar EHG recording techniques are more consistent in detecting the contractions recorded by IUP than the TOCO signal (contraction detection correlated better with IUP (0.94±0.06) than with TOCO 0.77±0.25 [8]). In the present work not only these findings that have been confirmed but also the fact that Laplacian recordings can detect more uterine contractions than TOCO. It should also be noted that Euliano only worked with monopolar recordings and to determine contraction consistency used the single monopolar EHG recording channel with the best signal-to-noise ratio of the four monopolar channels used. Similarly, Jezeweski selected the bipolar channel with the best results in the parametric identification of contractions [26]. Whereas in this work we presented the results of all the recording channels, showing that all of them presented better behaviour than TOCO in terms of detecting uterine contractions.

Although other parameters from pressure and EHG recordings may be used to further characterize uterine dynamics, such as duration of contractions, maximum peak, etc. and have been considered by other authors [4,6,9,10,32,33], , they are outside the scope of the present work.

4.2 EHG recording technique and electrode position

One of the most important limitations to the wider application of EHG recordings is the quality of the signals captured on the body surface. These signals are very weak and are subject to interference such as the mECG and baseline oscillations.

Diverse methods have been proposed to date to reduce maternal cardiac interference in electrohysterographic signals, including: methods of identifying mECG interference by generating PQRST templates of the maternal complex for its suppression during the maternal cardiac cycles [34], techniques based on dynamic mECG segmentation for subsequent linear prediction and elimination of the mECG segments [35,36] wavelets [31,37] and empirical mode decomposition [31]. This type of methods in general give satisfactory results, although they do require extensive computing power which, when combined with other factors makes their use difficult in real time monitoring and diagnostic systems. Adaptive filters may be used for such applications [38] but still they have to be applied to digitalised signals, and require computing power. In the present study, the Laplacian EHG signals (discrete estimation and signals from the active annular electrodes) present a higher signal-to-mECG interference ratio than the simultaneously acquired monopolar and bipolar recordings. Specifically, the highest S/I_{mECG} values correspond to signals captured by the active concentric annular electrodes, which agrees with previously published findings on the use of active annular electrodes for estimating the Laplacian of the electroenterographic potential on the abdominal surface [23]. Moreover, Laplacian recordings present signal-to-mECG interference ratios similar to those obtained from the above-mentioned signal processing techniques, but in this case without the need to digitalise and post-process the signal, which facilitates their direct application in real time monitoring systems.

On the other hand, the values obtained for the signal-to-noise ratio (S/N) agree with those presented in previous studies [31,39] for bipolar recordings. This parameter was found to vary widely not only between patients but also between contractions in the same patient. This is primarily due to the fact that the contractions detected can vary in intensity, and also to baseline changes caused, for example, by contact impedance variations when the patient changes position, in addition to variations in the intrinsic characteristics of individual patients, such as their BMI, week of gestation, etc. In any case, higher signal-to-noise ratios can be expected from bipolar than from monopolar recordings, given their capability to reduce common mode interferences (e.g. in the signal-to-mECG interference ratios). However, bearing in mind that the EHG signal propagation speed is approximately 8 cm/s during labour [40] and the interelectrode distance is 2.5 cm, some components of the signal under study can be cancelled in bipolar signals due to dips in the frequency spectrum which also depend on the main propagation direction. In the case of annular electrodes these dips also appear, but they are only affected by electrode's dimensions and conduction velocity, but not by propagation direction as reported by Farina et al [41]. The annular electrodes tested in this study proved to be suitable to detect uterine contractions. Furthermore, in spite of the wide variations observed in S/N parameters, the recordings from the active annular sensors again performed best in this aspect, suggesting that this technique also reduces common mode interferences while not cancelling much information of interest.

Regarding the optimum recording position, the literature favours the subumbilical uterine median axis because of a closer contact and a more constant position of the uterus relative to the abdominal wall during contractions [9, 25,33]. Our CCI results also indicate that the highest numbers of contractions are detected by both mono- and bipolar EHG recordings in this zone. It should be pointed out that the annular electrodes were placed in the supraumbilical zone for reasons of space and not above the uterine median but on either side of it. This factor, besides the fact that these electrodes are dry (no electrolytic gel is used providing higher skin electrode impedance about 1 kOhm) Seems to be the reason for the lower CCI values obtained from recordings made with this type of electrodes. It would therefore be of interest to create an additional database on the different locations for active annular electrodes. In addition considering that the tested annular electrodes were developed on rigid substrate which limits its adaptation to the body surface contours, the development of new versions of these electrodes on flexible substrates could yield better performance. Nevertheless, the proven capability of annular electrodes to detect uterine contractions is of great importance since this type of electrodes provides better spatial resolution recordings in comparison to monopolar and bipolar recordings carried out by conventional disc electrodes [17]. This can be a great advantage in electrohysterographic propagation analysis, which has recently proven to provide very valuable information for predicting preterm delivery [15,42] .

Another interesting question derived from the analysis of the results obtained is that the zone to the right of the uterine median axis seems to offer advantages as regards both signal quality indicators and detecting uterine contractions. This is in line with electrophysiological and anatomical studies that have shown that the uterus moves slightly to the right throughout pregnancy [43].

4.3 Limitations of the study

The present study focused on the active stage of labour in singleton pregnancies and the results should be compared with recordings taken in the final stages of pregnancies before the onset of labour, even though the intrauterine pressure recording (IUP) may not be available, and also with recordings from multiple pregnancies. In fact, recordings in the last weeks of pregnancy are now being performed. Also, the patients in the data base used in this study are limited in number and should be increased in future work.

The electrodes used in the EHG recording techniques studied were placed in different locations and the fact that those situated over the uterine subumbilical median axis probably had an unfair advantage could affect the interpretation of the results to some extent. In this regard, it would be interesting to obtain and analyse recorded signals from different positions (in our case turning the silicon template used to place the electrodes). The capacity to detect contractions of recordings taken from annular electrodes is likely to increase in other positions, especially when placed over the uterine median axis.

It should also be pointed out –as mentioned before- that the annular electrodes used to obtain the Laplacian estimation of the EHG surface potential were developed on rigid substrates, with a limited ability to adapt to the curves on the surface of the body, being difficult to ensure good skin-electrode contact and causing certain degree of discomfort to the patient. At the present time our research group is involved in the task of developing similar electrodes over flexible substrates, which are expected to further improve both signal quality and the overall performance of this recording technique.

5 Conclusions

This paper presents different techniques and electrode placements for recording EHG signals as an alternative to TOCO for non-invasive monitoring of uterine activity. The results show that all the EHG-based techniques are able to detect a higher number of uterine contractions than TOCO, especially from recordings taken over the uterine median axis.

Concerning the technology for EHG signal recordings, those from Laplacian recording techniques provide better quality signals than those obtained from the traditional mono- and bipolar techniques in terms of both reducing cardiac interference and enhancing the signal-to-noise ratio. The best position for placing EHG recording electrodes was found to be the uterine median axis and the centre-right subumbilical zone.

Acknowledgements

Research partly supported by the Spanish Ministerio de Ciencia y Tecnología (TEC2010-16945) and the Universitat Politècnica de Valencia (PAID 2009/10-2298). The translation of this paper was funded by the Universitat Politècnica de València, Spain.

REFERENCES

1. Bakker P, Kurver P, Kuik D, and Van Geijn H. Elevated uterine activity increases the risk of fetal acidosis at birth. American Journal of Obstetrics and Gynecology. 2007;**196:**313e1-313e6

2. Bakker PC, Van Rijsiwijk S, and van Geijn HP. Uterine activity monitoring during labor. Journal of Perinatal Medicine. 2007;**35:**468-477

3. Miller DA and Miller LA. Electronic fetal heart rate monitoring: applying principles of patient safety. American Journal of Obstetrics and Gynecology. 2012;**206:**278-283

4. Schlembach D, Maner WL, Garfield RE, and Maul H. Monitoring the progress of pregnancy and labor using electromyography. Eur.J.Obstet.Gynecol.Reprod.Biol. 2009;**144 Suppl 1:**S33-S39

5. Wilmink FA, Wilms FF, Heydanus R, Mol BW, and Papatsonis DN. Fetal complications after placement of an intrauterine pressure catheter: a report of two cases and review of the literature. J.Matern.Fetal Neonatal Med. 2008;**21:**880-883

6. Miles AM, Monga M, and Richeson KS. Correlation of external and internal monitoring of uterine activity in a cohort of term patients. American Journal of Perinatology. 2001;**18:**137-140

7. Eswaran H, Wilson JD, Murphy P, Preissl H, and Lowery CL. Application of wavelet transform to uterine electromyographic signals recorded using abdominal surface electrodes. The journal of maternal-fetal & neonatal medicine : the official journal of the European Association of Perinatal Medicine, the Federation of Asia and Oceania Perinatal Societies, the International Society of Perinatal Obstetricians. 2002;**11:**158-166

8. Euliano TY, Nguyen MT, Marossero D, and Edwards RK. Monitoring contractions in obese parturients: electrohysterography compared with traditional monitoring. Obstet Gynecol. 2007;**109:**1136-1140

9. Devedeux D, Marque C, Mansour S, Germain G, and Duchene J. Uterine electromyography: a critical review. Am.J.Obstet.Gynecol. 1993;**169:**1636-1653

10. Maul H, Maner WL, Olson G, Saade GR, and Garfield RE. Non-invasive transabdominal uterine electromyography correlates with the strength of intrauterine pressure and is predictive of labor and delivery. J.Matern.Fetal Neonatal Med. 2004;**15:**297-301

11. Marshall JM. Regulation of activity in uterine smooth muscle. Physiol Rev.Suppl. 1962;**5:**213-227

12. Garfield RE and Maner WL. Physiology and electrical activity of uterine contractions. Semin.Cell Dev.Biol. 2007;**18:**289-295

13. Rabotti C, Mischi M, Beulen L, Oei G, and Bergmans JW. Modeling and identification of the electrohysterographic volume conductor by high-density electrodes. IEEE Trans.Biomed.Eng. 2010;**57:**519-527

14. Karlsson, B., Terrien, J., Gudmundsson, V., Steingrimsdottir, T., and Marque, C. Abdominal EHG on a 4 by 4 grid: mapping and presenting the propagation of uterine contractions. IFMBE proceedings 2007;**1-2:**139-143

15. Rabotti C, Mischi M, Oei SG, and Bergmans JW. Noninvasive estimation of the electrohysterographic action-potential conduction velocity. IEEE Trans.Biomed.Eng. 2010;**57:**2178-2187

16. Hjorth B. An on-line transformation of EEG scalp potentials into orthogonal source derivations. Electroencephalogr.Clin.Neurophysiol. 1975;**39:**526-530

17. He B, Yu X, Wu D, and Mehdi N. Body surface Laplacian mapping of bioelectrical activity. Methods Inf.Med. 1997;**36:**326-328

18. He B, Lian J, and Li G. High-resolution EEG: a new realistic geometry spline Laplacian estimation technique. Clin.Neurophysiol. 2001;**112:**845-852

19. He B and Wu D. Laplacian electrocardiography. Critical Reviews in Biomedical Engineering. 1999;**27:**285-338

20. Lian J, Li G, Cheng J, Avitall B, and He B. Body surface Laplacian mapping of atrial depolarization in healthy human subjects. Med.Biol.Eng Comput. 2002;**40:**650-659

21. Lu CC and Tarjan PP. An ultra-high common-mode rejection ratio (CMRR) AC instrumentation amplifier for laplacian electrocardiographic measurement. Biomed.Instrum.Technol. 2002;**33:**76-83

22. Koka K and Besio WG. Improvement of spatial selectivity and decrease of mutual information of tri-polar concentric ring electrodes. J.Neurosci.Methods. 30-9-2007;**165:**216-222

23. Prats-Boluda G, Garcia-Casado J, Martinez-de-Juan JL, and Ye-Lin Y. Active concentric ring electrode for non-invasive detection of intestinal myoelectric signals. Med.Eng Phys. 2011;**33:**446-455

24. Besio WG, Koka K, Aakula R, and Dai W. Tri-polar concentric ring electrode development for laplacian electroencephalography. IEEE Trans.Biomed.Eng. 2006;**53:**926-933

25. Rabotti C, Mischi M, van Laar JO, Oei GS, and Bergmans JW. Estimation of internal uterine pressure by joint amplitude and frequency analysis of electrohysterographic signals. Physiol Meas. 2008;**29:**829-841

26. Jezewski J, Horoba K, Matonia A, and Wrobel J. Quantitative analysis of contraction patterns in electrical activity signal of pregnant uterus as an alternative to mechanical approach. Physiol Meas. 2005;**26:**753-767

27. Euliano TY, Nguyen MT, Darmanjian S, McGorray SP, Euliano N, Onkala A, and Gregg AR. Monitoring uterine activity during labor: a comparison of 3 methods. Am.J.Obstet.Gynecol. 2013;**208:**66-66

28. Hamilton PS and Tompkins WJ. Quantitative Investigation of QRS Detection Rules Using the MIT/BIH Arrhythmia Database. Biomedical Engineering, IEEE Transactions on. 1986;**BME-33:**1157-1165

29. Maner WL and Garfield RE. Identification of human term and preterm labor using artificial neural networks on uterine electromyography data. Ann.Biomed.Eng. 2007;**35:**465-473

30. Rabotti C, Mischi M, van Laar JO, Oei GS, and Bergmans JW. Inter-electrode delay estimators for electrohysterographic propagation analysis. Physiol.Meas. 2009;**30:**745-761

31. Hassan M, Boudaoud S, Terrien J, Karlsson B, and Marque C. Combination of Canonical Correlation Analysis and Empirical Mode Decomposition Applied to Denoising the Labor Electrohysterogram. I Biomedical Engineering, IEEE Transactions on. 2011;**58:**2441-2447

32. Haran G, Elbaz M, Fejgin MD, and Biron-Shental T. A comparison of surface acquired uterine electromyography and intrauterine pressure catheter to assess uterine activity. American Journal of Obstetrics and Gynecology. 2012;**206:**412.e1-5-

33. Marque CK, Terrien J, Rihana S, and Germain G. Preterm labour detection by use of a biophysical marker: the uterine electrical activity. BMC.Pregnancy Childbirth. 2007;**7 Suppl 1:**S5

34. Matonia A, Jezewski J, Horoba K, Gacek A, and Labaj P. The maternal ECG suppression algorithm for efficient extraction of the fetal ECG from abdominal signal. 2006 28th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, **1-15**. 2006;296-299

35. Vullings R, Peters C, Mischi M, Sluijter R, Oei G, and Bergmans J. Artifact reduction in maternal abdominal ECG recordings for fetal ECG estimation. IEEE EMBS Proceedings. 2007:43-46

36. Martens SMM, Rabotti C, Mischi M, and Sluijter RJ. A robust fetal ECG detection method for abdominal recordings. Physiological Measurement. 2007;**28:**373-388

37. Leman H and Marque C. Rejection of the maternal electrocardiogram in the electrohysterogram signal. IEEE Trans.Biomed.Eng. 2000;**47:**1010-1017

38. Marque C, Bisch C, Dantas R, Elayoubi S, Brosse V, and Perot C. Adaptive filtering for ECG rejection from surface EMG recordings. Journal of Electromyography and Kinesiology. 2005;**15:**310-315

39. Terrien J, Marque C, Steingrimsdottir T, and Karlsson B. Evaluation of adaptive filtering methods on a 16 electrode electrohysterogram recorded externally in labor. 11th Mediterranean Conference on Medical and Biomedical Engineering and computing. 2007;**16:**135-138

40. Rabotti C, Bijloo R, Oei G, and Mischi M. Vectorial analysis of the electrohysterogram for prediction of preterm delivery: a preliminary study. Conf.Proc.IEEE Eng Med.Biol.Soc. 2011;**2011:**3880-3883

41. Farina D and Cescon C. Concentric-ring electrode systems for noninvasive detection of single motor unit activity. IEEE Trans.Biomed.Eng. 2001;**48:**1326-1334

42. Lucovnik M, Maner WL, Chambliss LR, Blumrick R, Balducci J, Novak-Antolic Z, and Garfield RE. Noninvasive uterine electromyography for prediction of preterm delivery. Am.J.Obstet.Gynecol. 2011;**204:**228-10

43. Norwitz, R., Arulkumaran , S., Symonds, I., and Fowlie, A. 2007 Oxford American Handbook of Obstetrics and Gynecology Oxford University Press.

CAPTIONS

Figure 1: Configuration of surface electrodes for obtaining simultaneously five monopolar EHG recordings (M1-M5) and two Laplacian potential recordings using active concentric-ringed-electrodes (L1 and L2).

Figure 2: Abdominal surface recording during contractile period. Signals (descending order): IUP: intrauterine pressure, TOCO: Tocodynamometer, Monopolar: M1, Bipolar: B1, Discrete Laplacian: L_D, Laplacian: anular active electrode L2.

Figure 3: Abdominal surface recording during a period without uterine contractions. Signals (descending order): Monopolar: M1, Bipolar: B1, Discrete Laplacian: L_D, Laplacian: active concentric ring Laplacian L1, mECG: Maternal ECG.

Figure 4: Signal-to-mECG interference ratio in rest state for the different electrode arrangements and recording techniques.

Figure 5: Signal-to-noise ratio in contraction period for the different electrode arrangements and recording techniques.

Table 1: Demographic and clinical characteristics of participants.

Table 2: Contractions Consistency Index to compare TOCO, IUP, EHG.

Foot Note: N_E: Number of detected contractions in EHG or TOCO signal. N_C: Number of consistent contractions. Monopolar: M1, M2, M3, M4, M5, Bipolar: B1, B2, B3, B4, Discrete Laplacian: LD, Annular ringed electrode: L1, L2.

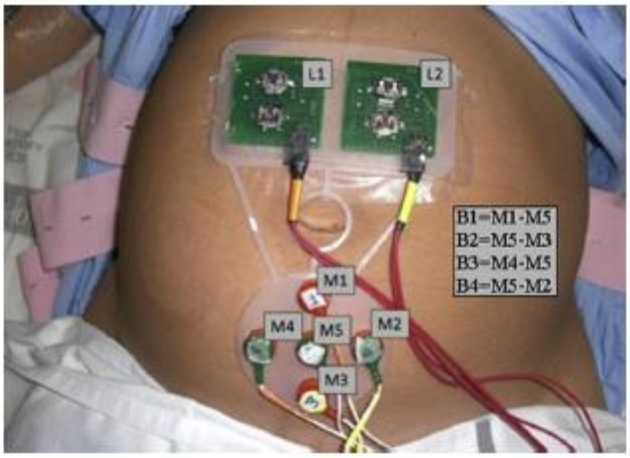

Fig. 1. Configuration of surface electrodes for obtaining simultaneously five monopolar EHG recordings (M1–M5) and two Laplacian potential recordings using active concentric-ringed-electrodes (L1 and L2).

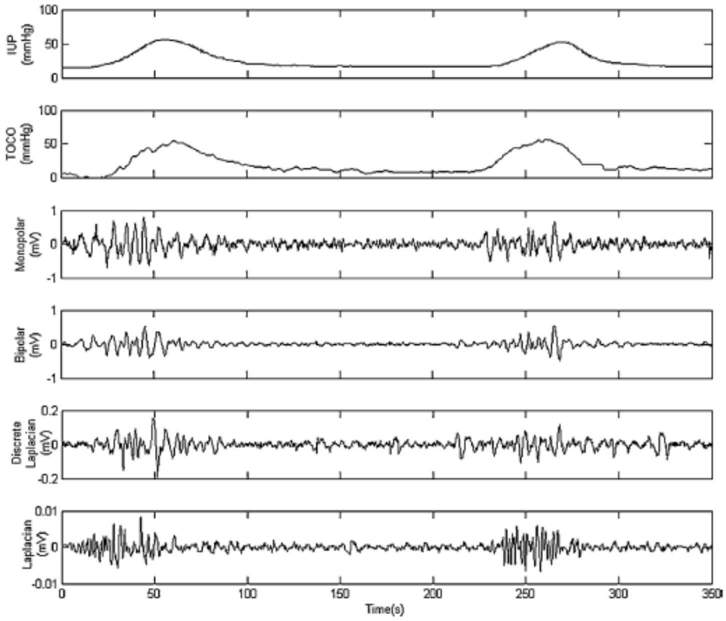

Fig. 2. Abdominal surface recording during contractile period. Signals (descending order): IUP: intrauterine pressure, TOCO: Tocodynamometer, Monopolar: M1, bipolar: B1, discrete Laplacian: L_D, Laplacian: anular active electrode L2.

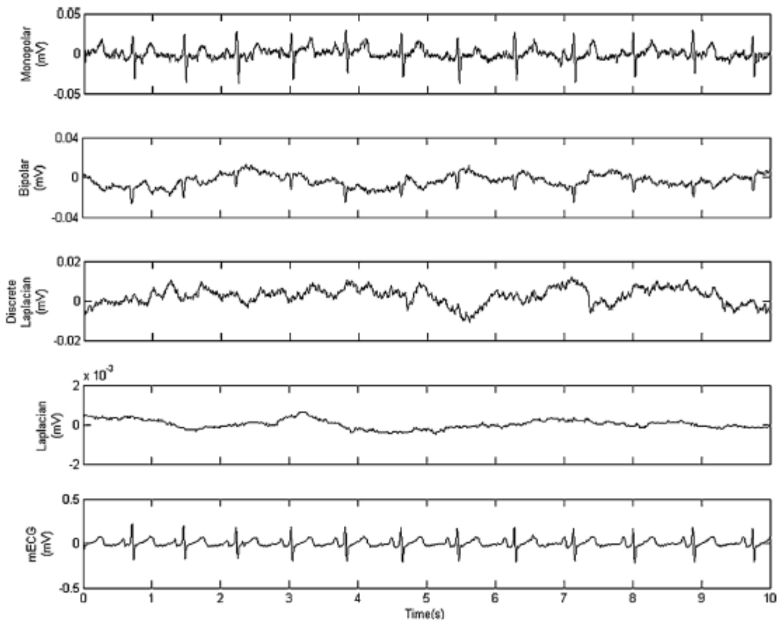

Fig. 3. Abdominal surface recording during a period without uterine contractions. Signals (descending order): monopolar: M1, bipolar: B1, discrete Laplacian: L_D, Laplacian: active concentric ring Laplacian L1, mECG: maternal ECG.

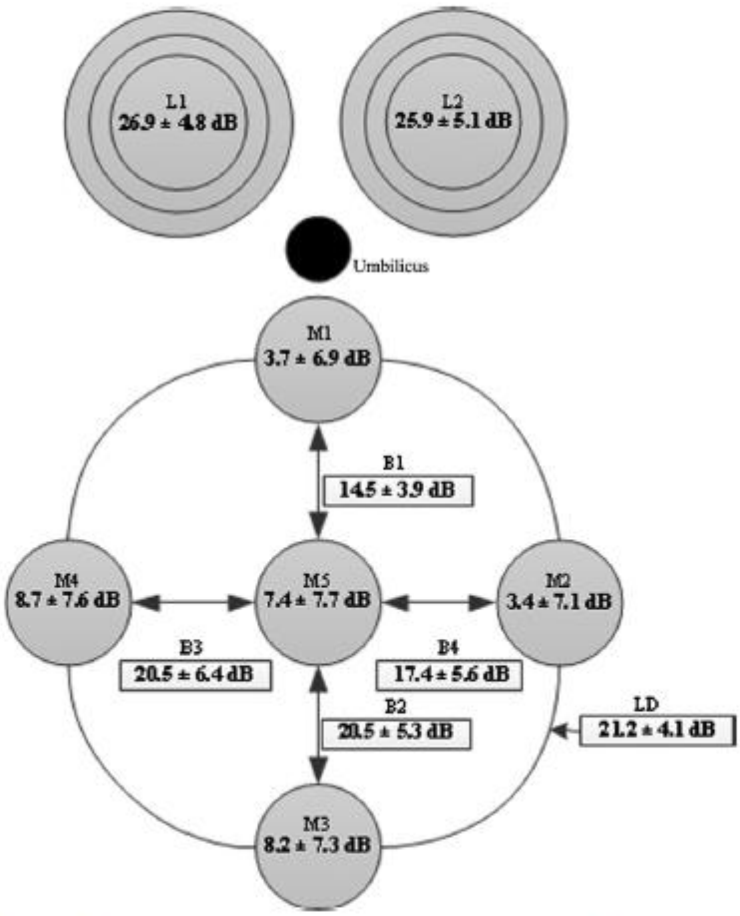

Fig. 4. Signal-to-mECG interference ratio in rest state for the different electrode arrangements and recording techniques.

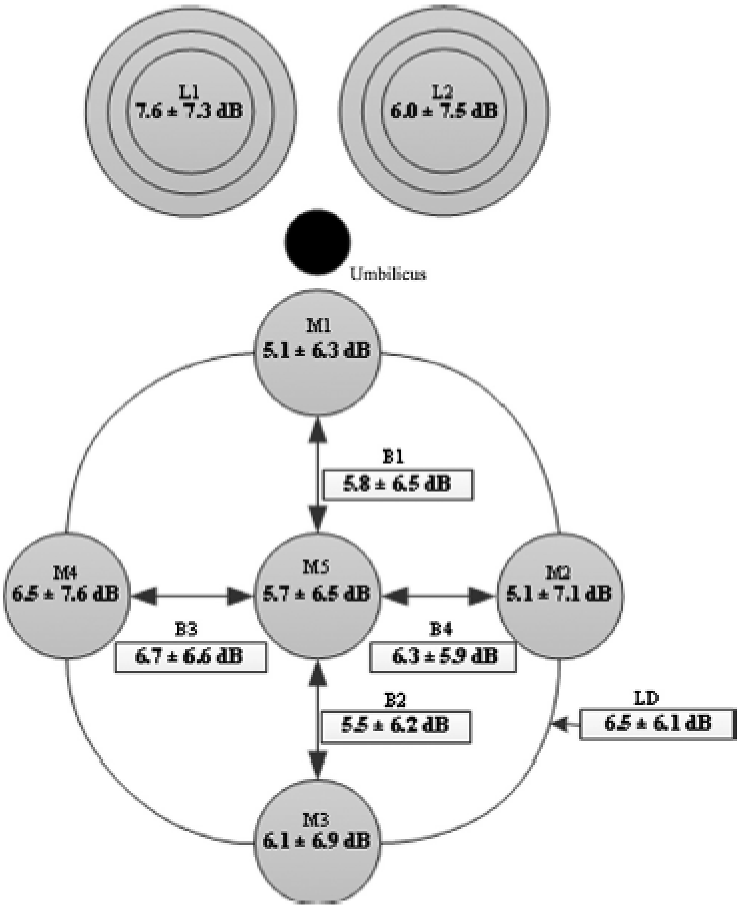

Fig. 5. Signal-to-noise ratio in contraction period for the different electrode arrangements and recording techniques.

Table 2
Contractions consistency index to compare TOCO, IUP and EHG.

Channel	N_T	N_E	CCI (%)
Contractions consistency index (CCI)			
M1	479	417	93.39
M2	479	384	89.30
M3	479	399	91.20
M4	479	382	89.04
M5	479	392	90.32
B1	479	423	94.10
B2	479	397	90.95
B3	479	404	91.82
B4	479	379	88.65
LD	479	384	89.30
L1	479	336	82.76
L2	479	288	75.39
TOCO	479	289	63.77

NE, number of detected contractions in EHG or TOCO signal; NC, number of consistent contractions; monopolar: M1, M2, M3, M4, and M5; bipolar: B1, B2, B3, B4; discrete Laplacian: LD, annular ringed electrode: L1, L2.

Table 1
Demographic and clinical characteristics of participants.

Parameter	Range	Average ± SD
Maternal BMI	23–36 kg/m^2	30.8 ± 4 kg/m^2
Parity	0–2	0.5 ± 0.8
Gestation	37 wk + 0 d ± 41 wk + 6 d	39 wk + 2 d ± 1 wk + 1 d
Initial cervical dilatation, cm	2–8 cm	3.5 ± 1.5 cm
Mode of delivery	No. of parturients	Percentage
Normal vaginal delivery	17	77.28%
Cesareansection	5	22.72%
Vacuum-assisted vaginal delivery	0	0
Augmentation of labour with oxytocin	22	100%