33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Classification Performance of the Frequency-Related Parameters Derived From Uterine EMG Signals

Moslem B., Karlsson B., Diab M.O., Khalil M. and Marque C.

Abstract – Frequency-related parameters derived from the uterine electromyogram (EMG) signals are widely used in many pregnancy monitoring and preterm delivery prediction studies. Although they are classical parameters, they are well suited for quantifying uterine EMG signals and have many advantages over amplitude-related parameters. The present work aims to compare various frequency-related parameters according to their classification performances (pregnancy vs. labor) using the receiver operating characteristic (ROC) curve analysis. The comparison between the parameters indicates that median frequency is the best frequency-related parameter that can be used for distinguishing between pregnancy and labor contractions. We conclude that median frequency can be the representative frequency-related parameter for classification problems of uterine EMG.

I. INTRODUCTION

Uterine electromyogram (EMG) recorded externally in pregnant women has been proven to be representative of the uterine contractility [1, 2]. Numerous studies have analyzed the uterine EMG recordings associated with pregnancy and labor contractions. It was reported that it is of interest to offer a good insight into the process of pregnancy and labor [3, 4]; therefore, it is potentially the best predictor of preterm labor [5, 6, 7]. Nowadays, classical statistical analysis in time and frequency domains has been widely explored. Temporal and spectral characteristics of the uterine EMG were defined in two physiological states: pregnancy and parturition. Some of these characteristics were used to monitor pregnancy and detect labor [7, 8]. Of particular interest has been the analysis of the frequency content of the uterine EMG recordings. Marque *et al.* [4] reported spectral changes of the uterine EMG from pregnancy to parturition. They concluded that pregnancy contractions are mainly characterized by low frequencies whereas labor contractions are related to the presence of higher frequencies. Similarly, Schlembach *et al.* [5] stated that, throughout pregnancy, there are measurable rise in the high-frequency content of the action potentials. They reported that the increases are favored by the changes that occur in the electrical properties of the myometrium during labor to increase contractile force in the myometrial smooth muscle. On the other hand, it was reported that frequency-related parameters are more suited to quantify the uterine EMG signals than the intensity independent parameters [9]. Therefore, they were chosen as the parameters of interest in various studies [5, 9]. The aim of this study is to compare the classification performances of different frequency parameters. Therefore, we compared the classification performances of four well known frequency-related parameters already used for the prediction of preterm labor: mean frequency, peak frequency, median frequency and the limit frequency that contains up to 95% of the energy in the power spectral density (PSD) noted "95%-limit frequency". These parameters were compared between each gestational situation, that is, pregnancy and labor using Receiver Operating Characteristic (ROC) analysis. The parameter with the best classification performance can be therefore selected for further use in classification studies.

Manuscript received June 20, 2011. This work is achieved in collaboration between the University of Technology of Compiègne in France and the Lebanese University in Lebanon.
Bassam MOSLEM and Catherine MARQUE are with the University of Technology of Compiègne – CNRS UMR 6600 Laboratoire Biomécanique et Bio-ingénierie, Compiègne, Cedex, France. (Corresponding author: +33 3 44 23 44 23, email: bassam.moslem@utc.fr).
Bassam MOSLEM and Mohamad Khalil are with the Lebanese University and the AZM center for research in biotechnology - Tripoli- Lebanon (Tel: +961 6 213255, email: bassam.moslem@ul.edu.lb)
B. Karlsson is with the School of Science and Engineering, Reykjavik University, Iceland.
Mohamad O. DIAB is with the Hariri Canadian University of Lebanon, College of Engineering.

II. METHODOLOGY

A. Database description:

Our analysis in this paper is based on digitized uterine EMG signals recorded on 32 women: twenty two were recorded during pregnancy (33 – 41 week of gestation, WG), seven during labor (37 – 42 WG) and three during both pregnancy and labor (33 – 42 WG). Recordings were made in the University Hospital of Amiens in France and at the Landspitali University hospital in Iceland by using a protocol approved by the relevant ethical committee (VSN 02-0006-V2). Recordings were performed by using a 16 electrode grid, arranged in a 4x4 matrix positioned on the women's abdomen [10] (fig.1). Signals were sampled at 200 Hz. The bursts of uterine electrical activity corresponding to contractions were then manually segmented. All the bursts presented a good signal to noise ratio on all bipolar channels.

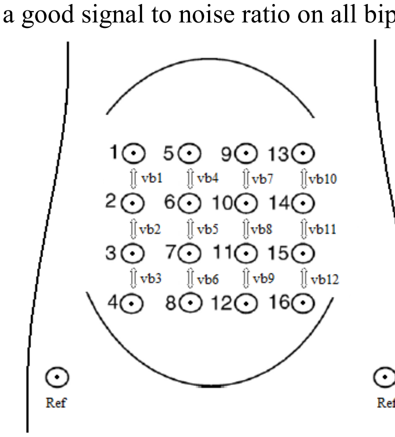

Fig. 1. Electrode configuration on the woman's abdominal wall.

B. Preprocessing:

Preprocessing is performed in two stages: first, unwanted signals were removed by filtering all the signals between 0.1 and 3 Hz. This bandwidth contains the main energy of the signals [1]; then, all signals were normalized [11].

C. Frequency-related parameters:

The power density spectrum (PSD) curve is a function of frequency and represents the relative contribution of each frequency to the signal. In our work, the PSD of each burst was obtained by using the fast Fourier transform. All parameters are then calculated from the power spectrum.

1) Mean frequency:

Mean frequency is calculated as the sum of the product of the power spectrum intensity and the frequency, divided by the total sum of the intensity of the PSD.

$$f_{mean} = \frac{\sum_{i=1}^{n} I_i . f_i}{\sum_{i=1}^{n} I_i} \quad (1)$$

Where n denotes the number of frequency components in the power spectrum, f_i the value of the frequency and I_i the intensity of the power spectrum corresponding to the frequency f_i.

2) Peak frequency:

Peak frequency is a common parameter used to evaluate the uterine electrical activity [9, 12]. The peak frequency of the signal power spectrum corresponds to the largest amplitude peak as determined by the power spectrum P of the uterine EMG signals. It is calculated as follows:

$$f_{max} = \arg\left(\frac{f_s}{N} max_{i=0}^{N-1} P(i)\right) \quad (2)$$

Where f_s and N denote the sampling frequency and the number of samples, respectively.

3) Median frequency:

The median frequency of the signal power spectrum, f_{med}, is defined as the frequency just above where the sums of the parts above and below in the frequency-power spectrum, P, are the same. The median frequency is calculated as follows:

$$f_{med} = i_m \frac{f_s}{N} \quad (3)$$

$$\sum_{i=0}^{i=i_m} P(i) = \sum_{i=i_m}^{i=N-1} P(i) \quad (4)$$

3) 95%-limit frequency:

Similarly to the median frequency, the 95%-limit frequency can be calculated from the PSD as the frequency just below where the frequency-power spectrum contains 95% of the total energy of the signal.

D. *Receiver Operating Characteristic (ROC) Analysis:*

In order to compare the classification performances of these parameters, the receiver operating characteristic (ROC) curve analysis was used. A ROC graph is a technique for visualizing, organizing and selecting classifiers based on their performances [13, 14]. ROC analysis has emerged therefore as an alternative metric for assessing classifiers. The ROC curve for binary classification plots the true positive rate (TPR) as a function of the false positive rate (FPR), that is, sensitivity against 1-specificity. ROC curves are compared by mean of the classic Area Under the Curve (AUC), accuracy (ACC), sensitivity (True positive rate), specificity (1-False positive rate) and the Matthews correlation coefficient (MCC). These measures from the curves are calculated as follows:

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \times 100 \quad (5)$$

$$MCC = \frac{TP \times TN - FP \times FN}{\sqrt{(TP + FN)(TP + FP)(TN + FP)(TN + FN)}} \quad (6)$$

$$True\ positive\ rate\ (TPR) = \frac{TP}{TP + FN} \times 100 \quad (7)$$

$$False\ positive\ rate\ (FPR) = \frac{FP}{FP + TN} \times 100 \quad (8)$$

Here *TP*, *FN*, *FP*, and *TN*, respectively, represent the numbers of true positives, false negatives, false positives, and true negatives.

III. RESULTS:

From each burst of uterine electrical activity corresponding to a contraction, the four frequency-related parameters were extracted. 50 contractions randomly selected of each class (labor vs. pregnancy) were used in this study. Since each contraction had a 12-channel resolution, we computed the values of the parameters over the 12-channel matrix related to each contraction then we determined their average over each contraction. As shown in figure 2, the frequency content significantly changes from pregnancy to labor. This figure illustrates the difference of the values of the mean frequency (fig.2.a), peak frequency (fig.2.b.), median frequency (fig.2.c.) and the 95%-limit frequency (fig.2.d.) between pregnancy and labor. The comparison between these two physiological states indicates that the values of all the parameters undergo significant changes from pregnancy and labor (tested by two-tailed student test: $p<0.05$). The mean values of the frequency parameters as well as the corresponding standard deviation in the two physiological states (pregnancy and labor) are shown in table 1.

Next, ROC curves corresponding to each frequency parameter were plotted and the parameters associated to the ROC curves were determined. Figure 3 shows the ROC curves generated from the values of each frequency parameter.

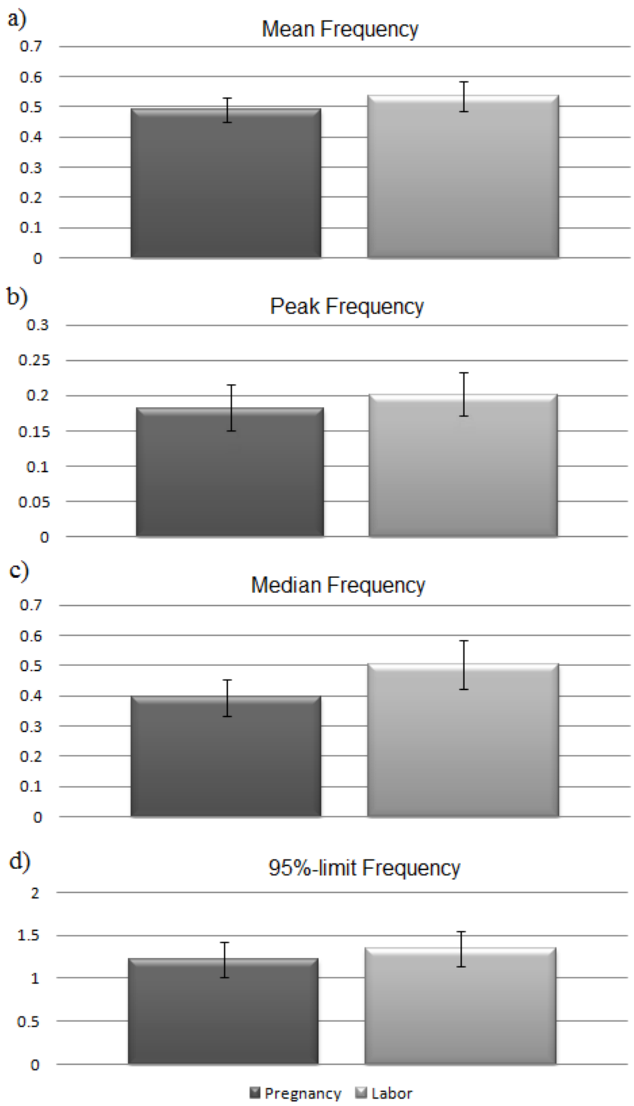

Figure 2 – The Difference between the four studied parameters in pregnancy (left) and labor (right): a) mean frequency, b) peak frequency, c) median frequency and d) the 95%-limit frequency. All parameters are expressed in Hertz.

Table 1 – Comparison between the values of the frequency parameters in pregnancy and labor

Frequency-related parameters	Pregnancy	Labor
Mean frequency	0.48±0.047	0.53±0.05
Peak frequency	0.18±0.06	0.2±0.05
Median frequency	0.39±0.06	0.5±0.06
95%-limit frequency	1.21±0.2	1.34±0.22

Visually, the median frequency showed the largest AUC. Similarly, the results illustrated in table 2 indicate that the median frequency has the highest AUC value (0.85). Table 2 shows that the corresponding sensitivity and specificity of the median frequency are 0.83 and 0.69 respectively; furthermore, median frequency had the highest values of the accuracy (ACC) and the Matthews correlation coefficient (MCC). On the other hand, the other frequency parameters showed all the same classification performance. As illustrated, median frequency is statistically better at identifying contractions than the other frequency parameters.

Table 2 – Comparison between the ROC parameters

Frequency-related Parameters	Sensi-tivity	Speci-ficity	AUC	ACC	MCC
Mean frequency	0.54	0.78	0.67	62.91	0.31
Peak frequency	0.72	0.54	0.66	65.72	0.26
Median frequency	0.83	0.69	0.85	78.4	0.53
95%-limit frequency	0.57	0.71	0.65	61.97	0.26

IV. DISCUSSION:

Frequency-related parameters, derived from the spectral analysis, have been used to evaluate questions related to obstetrical monitoring and preterm delivery prediction. It was demonstrated that these parameters are suitable for analyzing the uterine EMG recordings because they do not depend on the amplitude of the signal which seems to be affected by the distance of the electrodes from the pacemaker cells [15]. They can also give supplementary information about both excitation and propagation of electrical activity [1, 6]; therefore, they are good representatives of contraction efficiency and are more reliable in predicting delivery. In our work, we demonstrated that median frequency presented the most discriminant values between the two considered classes (pregnancy and labor). Therefore, we concluded that it is the most accurate frequency parameter for classifying uterine EMG signals. One possible explanation observable fact is that median frequency divides the PSD into two equal parts. Since there are significant spectral changes from pregnancy to parturition, median frequency can significantly increase, whereas, the other frequency parameters vary in small bandwidths. It's noteworthy to mention also that median frequency is a one of the most used parameters for the characterization of the surface EMG [16] which confirms its use for uterine EMG signals.

From our study as well as from others, it was demonstrated that peak frequency, mean frequency and the 95%-limit frequency increase slightly throughout pregnancy [9, 17, 18]. Thus, their variations remain irrelevant. Median frequency can therefore be applied in new approaches currently applied to monitor pregnancy and predict preterm delivery.

V. CONCLUSION:

In this paper, the classification performance of the frequency-related parameters was investigated using ROC analysis. Commonly-used parameters describing the frequency content of uterine EMG signals such as mean frequency, peak frequency, median frequency and the 95%-limit frequency were studied. We demonstrated that median frequency can be a representative frequency parameter since it remarkably showed the highest classification performance. We conclude that median frequency can be applied in new methods currently in use to monitor pregnancy as well as in classification problems.

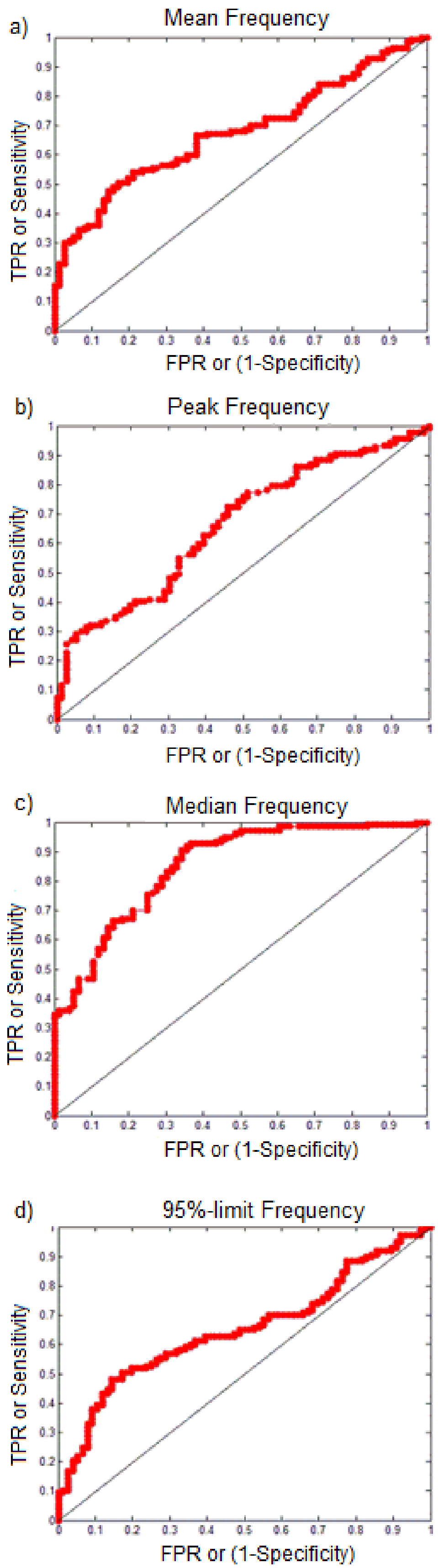

Figure 3 – ROC curves calculated from the frequency parameters: a) mean frequency, b) peak frequency, c) median frequency and d) the 95%-limit frequency

ACKNOWLEDGMENT

The authors wish to thank M. Charles Muszynski from University Hospital of Amiens in France for his help in the acquisition of the women uterine EMG recordings.

REFERENCES

[1] D. Devedeux, C. Marque, S. Mansour, G. Germain, and J. Duchene, "Uterine electromyography: a critical review," *Am J Obstet Gynecol,* vol. 169, pp. 1636-1653, Dec 1993.

[2] R. E. Garfield and W. L. Maner, "Physiology and electrical activity of uterine contractions," *Seminars in Cell & Developmental Biology,* vol. 18, pp. 289-295, 2007.

[3] J. Gondry, C. Marque, J. Duchene, and D. Cabrol, "Electrohysterography during pregnancy: preliminary report," *Biomed Instrum Technol,* vol. 27, pp. 318-324, Jul-Aug 1993.

[4] C. Marque, J. M. Duchene, S. Leclercq, G. S. Panczer, and J. Chaumont, "Uterine EHG processing for obstetrical monitoring," *IEEE Trans Biomed Eng,* vol. 33, pp. 1182-1187, Dec 1986.

[5] D. Schlembach, W. L. Maner, R. E. Garfield, and H. Maul, "Monitoring the progress of pregnancy and labor using electromyography," *European Journal of Obstetrics & Gynecology and Reproductive Biology,* vol. 144, pp. S33-S39, 2009.

[6] M. Doret, J. C. Pasquier, C. Gharib, and P. Gaucherand, "L'électromyogramme utérin : principes et intérêt pour le diagnostic de travail prématuré," *Journal de Gynécologie Obstétrique et Biologie de la Reproduction,* vol. 37, pp. 24-32, 2008. [French]

[7] C. Marque, J. Gondry, J. Rossi, N. Baaklini, and J. Duchêne, "Surveillance des grossesses à risque par électromyographie utérine," *RBM-News,* vol. 17, pp. 25-31, 1995. [French]

[8] H. Leman, C. Marque, and J. Gondry, "Use of the electrohysterogram signal for characterization of contractions during pregnancy," *IEEE Trans Biomed Eng,* vol. 46, pp. 1222-1229, Oct 1999.

[9] W. L. Maner, R. E. Garfield, H. Maul, G. Olson, and G. Saade, "Predicting term and preterm delivery with transabdominal uterine electromyography," *Obstet Gynecol,* vol. 101, pp. 1254-1260, Jun 2003.

[10] B. Karlsson, J. Terrien, V. Gudmundsson, T. Steingrimsdottir, and C. Marque, "Abdominal EHG on a 4 by 4 grid: mapping and presenting the propagation of uterine contractions," in *11th Mediterranean Conference on Medical and Biomedical Engineering and Computing 2007,* vol. 16, T. Jarm, P. Kramar, and A. Zupanic, Eds.: Springer Berlin Heidelberg, 2007, pp. 139-143.

[11] G. J. Lehman and S. M. McGill, "The importance of normalization in the interpretation of surface electromyography: a proof of principle," *J Manipulative Physiol Ther,* vol. 22, pp. 444-446, Sep 1999.

[12] R. E. Garfield and W. Maner, "Uterine Electromyography in Humans – Contractions, Labor, and Delivery," in *11th Mediterranean Conference on Medical and Biomedical Engineering and Computing*, 2007, vol. 16, pp. 128–130.

[13] A. Linden, "Measuring diagnostic and predictive accuracy in disease management: an introduction to receiver operating characteristic (ROC) analysis," *J Eval Clin Pract,* vol. 12, pp. 132-139, Apr 2006.

[14] T. Fawcett, "An introduction to ROC analysis," *Pattern Recognition Letters,* vol. 27, pp. 861-874, 2006.

[15] S. Rihana, E. Lefrancois, and C. Marque, "A two dimension model of the uterine electrical wave propagation," *Conf Proc IEEE Eng Med Biol Soc,* vol. 2007, pp. 1109-1112, 2007.

[16] H. J. Hermens, T. A. M. v. Bruggen, C. T. M. Baten, W. L. C. Rutten, and H. B. K. Boom, "The median frequency of the surface EMG power spectrum in relation to motor unit firing and action potential properties," *Journal of Electromyography and Kinesiology,* vol. 2, pp. 15-25, 1992.

[17] B. Moslem, M. Hassan, M. Khalil, C. Marque, and M. O. Diab, "Monitoring the progress of pregnancy and detecting labor using uterine electromyography," in *Proceedings of the International Symposium on Bioelectronics and Bioinformatics*, 2009, pp. 160-163.

[18] R. E. Garfield, W. L. Maner, H. Maul, and G. R. Saade, "Use of uterine EMG and cervical LIF in monitoring pregnant patients," *BJOG,* vol. 112 Suppl 1, pp. 103-108, Mar 2005.