Computer Simulation of Uterine Contraction Dynamics

Kemal Aydin[1], Tansel Halic[1], Coskun Bayrak[2], Kamran Iqbal[3]
[1]Dept. of Applied Science, [2]Dept. of Computer Science, [3]Systems Engineering Dept.
University of Arkansas at Little Rock
2801 S. University Ave., Little Rock, AR 72204
USA

Abstract: - The aim of this study is to simulate the contraction phenomena in pregnant uterine. Differential equations are used to model the uterine contractions for three states, namely contracting, refractory, and resting. Since verification and validation are vital for simulation systems, we compared our model with uterine magnetomyogram (MMG) data which are recorded non-invasively using SQUID-Array for Reproductive Assessment (SARA) system at University of Arkansas for Medical Sciences (UAMS). It is possible to identify the contraction locations from the data via Hilbert-Huang Transform (HHT). Two simulations were done; first one was based on the mathematical model and the second one was based on the contraction data. Comparison between those simulations revealed similar characteristics.

Key-Words: - Nonlinear signal processing, Differential Modeling, Uterine Contraction

1 Introduction

The aim of this work is to simulate uterine contractions with a mathematical model and then compare the results with contraction data to gain better understanding of the myometrial activities. Prematurity contributes to 75% of all deaths in newborns [1,2,3]. There may be a pattern in the uterine contractions or in their coordination which can reveal whether or not a contraction will lead to a delivery. This complex phenomenon is still a challenge for the researchers.

Current methods of data recordings for understanding uterine contractions include TOCO (tocodynamometers) and IUPC (Intra Uterine Pressure Catheter)[4]. TOCO uses the frequencies of the uterine contractions. On the other hand, IUPC uses the intrauterine pressure which is more reliable because, it is objective in the sense that wherever IUPC has a high pressure there must be a contraction in the uterine muscles at that time, which is the source of that pressure. The major drawback of IUPC is its invasive nature and that it can be used only after the rupture of the membranes.

In this work, two simulations were carried out. First one is the mathematical simulation which mimics the cooperation between the cells during pregnancy and the periodic nature of the contractions. Second one is the simulation of real uterine contractions which is based on the Hilbert-Huang Transform (HHT) of the signals and location data of the sensors.

2 Materials and Methods

2.1 Data Recording

Uterine MMG signal was recorded from pregnant patients at the gestational ages of 32 to 38 weeks. The study was approved by University of Arkansas for Medical Sciences (UAMS) Human Research Advisory Board and was performed after obtaining written consent from each patient. Due to the invasive nature of IUPC recording, it was done for only one patient so far.

Transabdominal MMG signals were recorded with the SARA (CTF Systems Inc) system with 151 primary magnetic sensors spaced approximately 3 cm apart over an area of 850 cm2. The sensors are arranged in a concave array that spans the maternal abdomen longitudinally from the symphysis pubis to the uterine fundus and a similar distance laterally.
The recording time varies from 12 to 28 minutes. The sampling rate is 250 Hz. The data were down-sampled to 25 Hz to reduce the computational complexity and post processed with a bandpass filter (0.05 - 1 Hz) since the uterine contraction activity is a band limited process (0.05 to 1 Hz) [5].

2.2 Mathematical Modeling

Basic Uterine contraction is modeled by Vague et al [6]. The set of differential equations define three states of myometrial uterine cells as active state, recovery state, and resting state. According to the

model, resting state cells are the cells that are available for contraction. Some of the resting state cells are selected randomly to initiate the contraction. They become active cells and they excite their neighbors. As time t advances, the contraction phase finishes for some cells and those cells move to the recovery phase. All cells that are in recovery phase advance to the resting state.

The differential equations for the uterine contraction model were stated by Vague et al. as the following:

$$\frac{dn_1}{dt} = \alpha.n_3(t) - \frac{n_1(t)}{\tau} \quad (1)$$

$$\frac{dn_2}{dt} = \frac{n_1(t)}{\tau} - \frac{n_1(t-T)}{\tau} \quad (2)$$

$$\frac{dn_3}{dt} = \frac{n_1(t-T)}{\tau} - \alpha.n_3(t) \quad (3)$$

$$n_1(t) + n_2(t) + n_3(t) = TotalCells \quad (4)$$

The model parameter α is assumed to be a constant variable that defines the excitability of the cells. "n_1" represents active cells, "n_2" represents recovering cells, "n_3" represents resting cells. T is the duration of the refractory period, and τ is the duration of the contraction period.

2.3 Uterine Data Simulation

Our objective is to determine locations of the contractions in time for each channel. By the help of HHT, we can localize any contraction event in time. HHT has two major steps. The first step is to preprocess the data by the empirical mode decomposition (EMD) method. The second step is to apply the Hilbert transform to the decomposed Intrinsic Mode Functions (IMFs) and construct the energy-frequency-time distribution, designated as the Hilbert Spectrum, from which the time localities of events are preserved [7]. The local energy derived from the data through the Hilbert transform gives us the contraction locations. This information then used to compose a spatio-temporal simulation of the uterine contractions.

3 Results

Two simulations were carried out. First one is based on mathematical model and the second one is based on real data. Second simulation shows spatio-temporal contractions of pregnant uterine.

3.1 Mathematical Model Simulation

Contractions are simulated with the help of a set of differential equations which were noted before. An application is written with OpenGL library to simulate contractions of cells. In this simulation, all cells are initially in resting phase. During simulation, randomly selected cells start contractions and they activate the neighborhood cells according to their excitability factor that is multiplied by the "Effective Area" parameter. Therefore the cells positions that are within the Effect Radius are propagated to the contraction state.

$$\text{Effect Radius} = \alpha.\text{Effective Area} \quad (5)$$

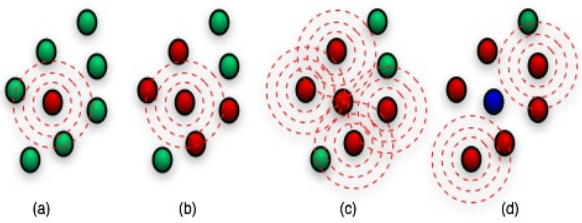

Fig. 1 (a) Initiator cell of a contraction is shown in red color which represents active cells (b) active cells trigger their immediate neighbors and force them to active stage, (c) each active cell tries to excite its immediate neighbors, (d) after a period of time active cells go into refractory stage which is shown in blue color.

Figure 1 shows schematic view of the initial contraction and its propagation over the neighborhood cells. In the simulation, cells within the effective area of an active cell are equally excited regardless of their distance to the triggering cell. A contracted cell can not be excited again until it turns into the resting stage.

The Figure 2 shows screenshots of the model simulator. Contraction starts at a location, then it propagates and then eventually it dies out. Contracted cells (red ones) are in active stage. Later on they go into refractory stage (blue ones) and then resting stage (green ones).

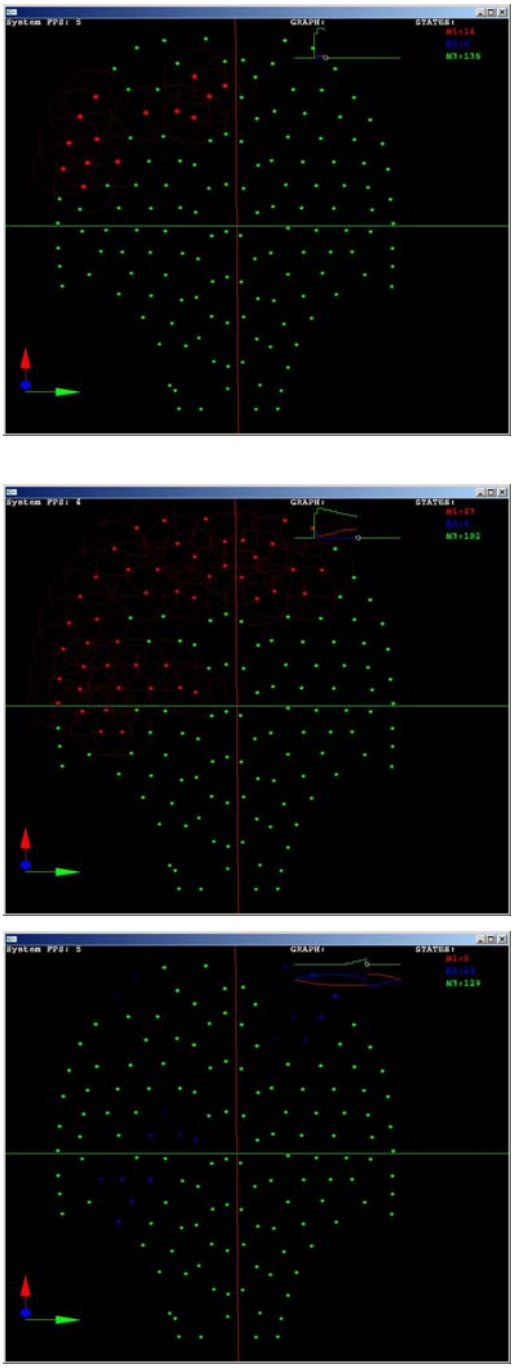

Fig. 2. Mathematical Model Simulation. The cell contractions are propagated across their neighbors according to the excitability factor of each cell which is defined as a constant in this case. Red, blue and green spheres represent active (n1), recovery (n2), and resting (n3) states respectively.

3.2 Spatio-temporal Contraction Simulation

In order to facilitate the comparison of the result with mathematical model, we compose a movie from the results of HHT.

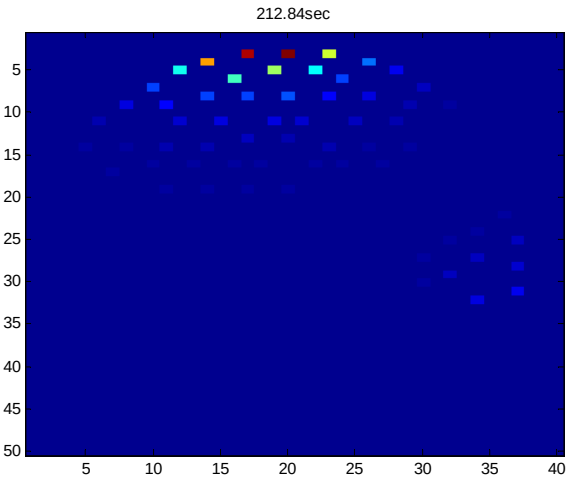

Fig. 3. Spatio-Temporal Contraction Simulation (t=212 sec)

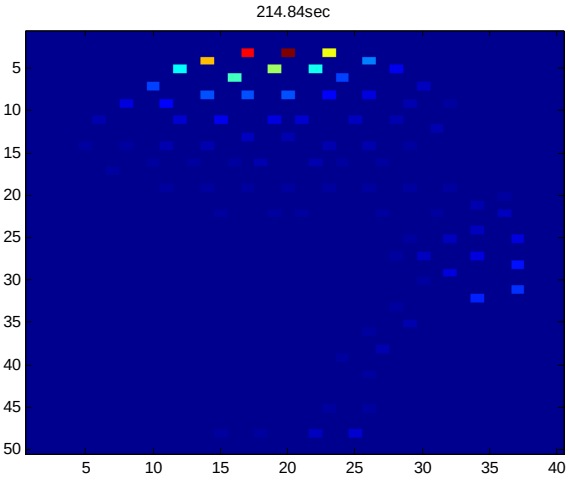

Fig. 4. Spatio-Temporal Contraction Simulation (t=214 sec)

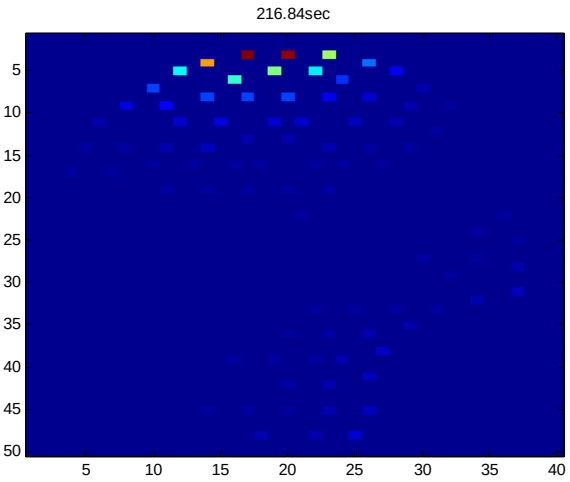

Fig. 5. Spatio-Temporal Contraction Simulation (t=216 sec)

We select 4 consequent points with 2 seconds difference which shows a sample propagation of a contraction in the figures. One artifact we encountered during the simulation was the upper part of the figures (Fig 3-5) which include maternal breathing artifact because upper sensors are closer to maternal lungs. Since maternal lungs produces a more intense MMG than myometrial muscles upper sensors appeared more dominant in our figures. If we neglect them we can watch the spread of contractions in the middle and lower parts of the pregnant mother's abdomen. Figure 3 has a contraction which is newly starting on the middle right part of the figure. On Figure 4, this contraction propagates from right to lower middle. On Figure 5, while the contracting cells at the starting point of contraction start to decrease, the contracting cells population in the lower middle start to increase.

4 Conclusion

In this work, we built two computer simulations. First one was a simulation of uterine contraction dynamics based on a set of differential equations. Second one was a simulation of real uterine contraction, in which HHT is used to identify contractions from the signal. We did verification and validation of the mathematical model by figurative comparison and we found that mathematical model of uterine contraction dynamics represents basic characteristics of the physiological phenomena of uterine contractions.

5 Acknowledgement

This research is partly supported by National Institute of Biomedical Imaging and Bioengineering (NIBIB) of National Institute of Health under the grant number 1R33-EB00978-02.

References:

[1] Baltimore, MD: Williams and Wilkins, "Guide to clinical preventative services: An assessment of the effectiveness of 169 interventions", U.S. Preventative Services Taskforce (1989).

[2] Brown, E.R. & Epstein,M., "Immediate consequences of preterm birth., In: Preterm Birth: Causes, Prevention, and Management.", Eds. Fuchs, F. & Stubblefield, P.G. New York: McMillan Publishing, 323, 1984.

[3] Brown, E.R., "Long-term consequences of preterm birth., In: Preterm Birth: Causes, Prevention, and Management." Eds. Fuchs, F. & Stubblefield, P.G. New York: McMillan Publishing, 333, 1984.

[4] Radhakrishnan N, Wilson JD, Lowery C, Eswaran H, Murphy P., "A fast algorithm for detecting contractions in uterine electromyography.", IEEE Eng Med Biol Mag. ,Mar-Apr;19(2):89-94, 2000.

[5] Eswaran, H., Preissl, H., Wilson, J., D., Murphy, P., & Lowery, C., L., Prediction of labor in term and preterm pregnancies using non-invasive magnetomyographic recordings of uterine contraction, J. Obstet. Gynecol., 190, ppp 1598-1603, 2004

[6] Vauge C, Carbonne B, Papiernik E, Ferre F., "A mathematical model of uterine dynamics and its application to human parturition", Acta Biotheor. Jun;48(2):95-105, 2000

[7] Norden E. Huang, Zheng Shen, Steven R. Long, Manli C. Wu, Hsing H. Shih, Quanan Zheng, Nai-Chyuan Yen, Chi Chao Tung and Henry H. Liu, "The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis", The Royal Society, 454, pp 903-995, 1998