Original Article

Emotional Changes in Fetuses and Mothers over the Course of Pregnancy: Chaos Analysis of Heart Sounds

Ishiyama Sayuri, RN, NM, PHN
Associate Professor, Department of Women's Health & Reproductive Health, The Japanese Red Cross Kyushu International College of Nursing, Fukuoka, Japan

Tahara Takashi, MD, PhD
CEO of Institute for Basic Medical and Welfare Research, Fukuoka, Japan

Iwanaga Hiroaki, SE
Institute for Basic Medical and Welfare Research, Fukuoka, Japan

Kiyooka Yoshiko, RN, NM
Professor, Department of Women's Health & Reproductive Health, The Japanese Red Cross Kyushu International College of Nursing, Fukuoka, Japan

Ohashi Kazutomo, MD, PhD
Professor, Faculty of Global Nursing, Otemae University, Osaka, Japan

Correspondence: Ohashi Kazutomo, MD, PhD, Professor, Faculty of Global Nursing, Otemae University, 6－42 Ochayashotyou Nsinomiya, Hyougo,662-8552, Japan. E-mail: ohashi@otemae.ac.jp

Abstract

Background: In the present study, we analyzed stimulus-induced emotional changes in fetuses and mothers by using the Lyapunov exponent (hereafter λ_1) and attractors.
Objective: We also investigated how emotions change in fetuses and mothers over the course of pregnancy.
Methodology: We measured heart sounds under five conditions: without external stimulation, while the mother's recorded voice was being heard, after the mother's recorded voice had finished being heard ,while a stranger's recorded voice was being heard and after the stranger's recorded voice had finished being heard. We used one-way analysis of variance to analyze differences among the λ_1 of fetal and maternal heart sounds under these five conditions. To observe the time-series characteristics of emotional responses, we calculated the moving average of the numbers of significantly different condition pairs.
Results: Based on moving average results, we confirmed three emotional phases in fetuses and mothers. Fetal phase I was around 20 weeks of pregnancy, phase II was from around 21 weeks of pregnancy to around 26 weeks, and phase III was from around 27 weeks to before birth.Maternal phase I occurred at around 19 weeks of pregnancy, phase II was around 20 weeks to 26 weeks, and phase III was from around 27 weeks to before delivery.Fetal attractors did not change in response to strangers' vocal stimuli but did change dramatically in response to mothers' vocal stimuli from Phase I to Phase III, from nearly structureless attractors to chaotic attractors. Maternal attractors were consistently chaotic attractors from Phase I to Phase III and exhibited little change over the course of pregnancy. Changes in fetal and maternal attractors under different conditions suggested the occurrence of entrainment.
Conclusions: The above results conceivably arise from the self-organization ability of fetuses and mothers.

Keywords: heart sound, emotion, chaos analysis, attractor, lyapunov exponent, deterministic chaos, phase transition

Background

Heart sounds generally reflect emotion (Valins, 1966). The present study uses chaos analysis of fetal and maternal heart sounds to analyze fetal and maternal emotions. Emotions are produced primarily in the limbic system and involve other areas of the brain such as the amygdala. A subject's emotions can be assessed by observation of their behaviors, facial expressions, autonomic nervous system, or endocrine system. Heart sounds, which are controlled by the subject's autonomic nervous system and endocrine system, reflect the subject's emotions quite clearly. According to chaos/complexity theory, the most defining characteristic of deterministic chaos is that it is equipped with self-organization ability (Haken, 1981).

In a previous study in which we measured the fetal and maternal heart sounds, we demonstrated that both sets of heart sounds exhibit deterministic chaos with self-organization ability (Ishiyama, 2018). Chaos theory has previously been invoked in studies using fetal heart rate to monitor health status (Chaffin, Goldberge & Reed, 1991; Kikuchi et al., 2006; Hoh et al., 2007).

However, the chaos analysis used in these studies suffered from problems with dimensional analysis methods and the construction of attractors.In the present study, we analyzed stimulus-induced emotional changes in fetuses and mothers by using the Lyapunov exponent (hereafter λ_1) and attractors. And we discussed the dynamics of emotional changes in fetuses and mothers over the course of pregnancy.

Methods

Subjects

The subjects were four healthy singleton pregnant women (A, B, C, D) without comorbidities and their fetuses. Two of the women were primiparous, while two were multiparous. The four mothers' ages ranged from 27 to 37 years. The study was conducted from March 2012 to February 2013 with the approval of the Institutional Review Board of the Japanese Red Cross Kyushu International College of Nursing (Approval No. 12-06).

Subjects provided written consent to participate in the study following oral and written explanations of the purpose of the study, measurement methods, the voluntary nature of participation, the freedom to withdraw from the study, benefits and detriments of participation, protection of personal information and experiment data, securement of confidentiality, result disclosure methods, and preservation and destruction of data.

Data collection

Measurement timing/location and vocal stimulus conditions

Heart sounds were measured every 2–4 weeks from 11 to 36 weeks of gestation. All measurements were performed in the same quiet private room maintained at a temperature of 23°C and roughly 50% humidity. In accordance with the methods used by Kisilevsky et al. (2003), after women lay in bed in the semi-Fowler's position for 5 min, their fetuses were subjected to each of the following five conditions for 1 min each (5 min total):
1)without external stimulation(Rest; R),
2) while the mother's recorded voice was being heard(Voice1;V1),
3)after the mother's recorded voice had finished being heard(After;A1) ,
4)while a stranger's recorded voice was being heard(Voice2:V2) and after the stranger's recorded voice had finished being heard(After2 :A2).In the present study, vocal stimuli consisted of mothers' voices and a stranger's voice. To ensure that vocal stimuli were consistent across all measurements, the mothers and a single stranger were recorded reading the same sentences. These sentences expressed concern for the fetus; for example, "How are you doing, baby? Are you feeling good inside mommy's tummy?".For each measurement, the above two vocal stimuli were played for 1 min at 60 dB from a recording device placed roughly 5 cm from the mother's abdomen.

Heart sound data collection

We developed a heart sound measurement system based on the methods used by Tsuda et al. (1992). Using two ultrasonic Doppler devices (Doppler Fetus Detector FD-390, TOITU CO., LTD., Tokyo, Japan), we simultaneously measured fetal heart sounds from the mother's abdominal wall and maternal heart sounds from the mother's chest. Fetal and maternal heart sounds obtained with the Doppler technique were converted from analog to digital format at a sampling rate of 1 KHz and a 16-bit depth and recorded with a logger program.To confirm that one cycle of heart sounds measured with an ultrasonic Doppler detector matched one cycle on an electrocardiogram, we simultaneously conducted ultrasonic Doppler measurement and electrocardiography in an adult man.

Chaos analysis

Lyapunov exponent (λ)

After performing correlation dimension analysis based on the method described by Grassberger & Procaccia (Grassberger & Procaccia, 1983a, 1983b), we performed Lyapunov spectrum analysis for fetal and maternal heart sounds. λ was calculated with the method described by Tsuda et al. (1992), which improved on the method used by Sano & Sawada (1985). The equation used to calculate λ is shown below.

$$\lambda = \lim_{t \to \infty} \frac{1}{t} \log_2 f(t)$$

where *f(t)* is the rate at which the two trajectories diverge with time.

As reported in our previous studies, we have found that the heart sounds of the fetus and its mother are five-dimensional, therefore, we calculated λ for each of these dimensions (λ_1, λ_2, λ_3, λ_4, λ_5) at 10s intervals during the 60s measurement period ,and the heart sound λ_1 values of the fetus and mother are positive (Ishiyama et al., 2018).λ_1 is the deterministic chaos that best reflects the characteristics of the system (Lorenz, 1993),and that a positive λ_1 is considered to indicate a state of deterministic chaos, we focused our attention on λ_1 and calculated the mean and standard deviation.

Attractor construction

In the field of dynamical systems, an attractor is a value or set of values toward which variables tend to move; it is a key component demonstrating that the system is a chaos or complex system. To construct the attractors, we embedded the data for dimensional configuration. Attractors were extracted in accordance with the methods of Grassberger and Procaccia (1983a, 1983b) by using a process of embedding. The chaos of fetal and maternal heart sounds is five-dimensional (Ishiyama, 2018). Therefore, we observed them from various angles on a computer, and analyzed them from different perspectives. The extracted attractor was projected in three dimensions which was cast into two dimensions in figures.

Statistical analysis

To examine differences in heart sound λ_1 between the no-stimulus condition (R) and other conditions (V1, A2, V2, A2), we performed one-way analysis of variance (ANOVA) for R-V1, R-A1, R-V2, and R-A2. To examine differences in heart sound λ_1 between the mother's voice condition (V1) and the stranger's voice condition (V2), we performed one-way ANOVA for V1-V2. $P < 0.05$ represented statistical significance.

Results

Table 1 shows ANOVA results for heart sound λ_1 between conditions for the four fetuses and their mothers. The absence of significant differences in λ_1 between pairs of conditions likely indicated that there was a form of emotional interaction between the two conditions, rather than them being independent of each other. In this light, on the basis of the ANOVA test results, we expected that there would be some groups (i.e., clusters) with significant differences. To elucidate this possibility, we plotted the numbers of pairs of conditions significant differences for each week of pregnancy. Furthermore, to eliminate noise, we used a 3-week moving average to partition the data. We used the differences in the values of the moving averages to determine the degree of change in the number of pairs that did differ significantly.

An examination of the moving average (solid line) for fetuses in Figure 1 reveals that the average is divided into three groups (delineated by vertical black lines) with borders at 20 and 27 weeks of gestation. These three groups were as follows: up to around 20 weeks of gestation, from around 21 to 26 weeks, and from around 27 weeks to delivery. Each group is an assemblage of conditions with significant differences and constitutes a statistically distinct set. The groups are clusters that reflect emotional states. Therefore, we defined these clusters as distinct emotional phases, which we designated Phase I, Phase II, and Phase III.

Figure 2 shows the moving average (solid line) for mothers calculated in the same manner as for fetuses.

As Figure 2 shows, the moving average is divided into three groups (represented with vertical black lines) with borders at around 19 and 27 weeks of gestation. These three groups were as follows: up to around 19 weeks of gestation, from around 20 to 26 weeks, and from around 27 weeks to delivery. As with fetuses, these three clusters for mothers were termed emotional phases and named Phase I, Phase II, and Phase III.Thus, we found that during pregnancy, fetuses and their mothers go through three emotional phases defined by major qualitative changes and divided by two borders.

Results for attractors were as follows. We extracted 260 attractors for fetal and maternal heart sound measurements conducted under all five conditions. When we examined changes in attractors for the four fetuses and their mothers by phase and condition, we found that all subjects demonstrated similar trends. Therefore, we have presented attractors for mother A and her fetus as examples (Figs. 3 & 4).

Examination of changes over time in the fetal attractors for V1 seen in Figure 3 reveals that, whereas the attractor in Phase I indicates nearly structureless chaos, as time passes into Phase II and Phase III, the attractor approaches nearly chaos or transforms into a chaotic attractor. Next, we similarly examined differences between V1 and A1 in the same phase. In Phase I, the attractors during and after the mother's voice stimulus were nearly structureless. However, in Phase II and Phase III, the attractor for after vocal stimulus approached nearly chaos or transformed into a chaotic attractor. Examination of changes over time in the fetal attractors for V2 in Figure 4 revealed that the attractor was nearly structureless throughout Phases I, II, and III.

Next, we similarly examined differences between V2 and A2 in the same phase. Throughout Phases I, II, and III, attractors were nearly structureless. Thus, in response to their mothers' voices, fetal attractors approached nearly chaos or transformed into chaotic attractors but demonstrated little change in response to a stranger's voice.

In contrast, when we examined changes in maternal attractors (Fig. 3 and 4), we found that attractors for V1 and V2 were consistently chaotic attractors throughout Phases I, II, and III. Similarly, attractors for V1 and A1 and for V2 and A2 were consistently chaotic attractors. Thus, maternal attractors did not differ markedly between their own voices and a stranger's voice.

In addition, when we examined changes in attractors between fetuses and mothers, we observed attractors for different conditions that resembled each other. To summarize the above, attractors for fetuses changed little over time in response to a stranger's voice but became increasingly chaotic in response to their mothers' voices. From Phase I to Phase II and Phase III, attractors approached nearly chaos or transformed into chaotic attractors. Maternal attractors were consistently chaotic attractors across all three phases, both in response to their own voices and to a stranger's voice.

Table 1. Results for one-way ANOVA of fetal and maternal heart sound λ_1 (four cases)

	condition \ wks.	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Fetus	R−V1	−	ND	*	*	ND	−	*	*	ND	*	*	*	*	*	−	*	−	*	*	ND	*	*	ND	*	ND	*
	R−A1	−	ND	*	*	ND	−	*	−	ND	−	*	*	−	*	−	−	−	−	*	ND	−	−	ND	*	ND	−
	R−V2	*	ND	*	*	ND	−	*	−	ND	*	*	−	*	−	*	*	−	*	*	ND	*	*	ND	*	ND	−
	R−A2	*	ND	*	*	ND	−	*	−	ND	*	−	*	−	*	−	*	−	*	−	ND	−	*	ND	−	ND	−
	V1−V2	−	ND	*	*	ND	−	−	−	ND	−	−	*	−	*	*	*	−	*	*	ND	−	*	ND	*	ND	−
Mother	R−V1	−	ND	−	*	ND	*	−	−	ND	*	*	*	−	*	−	−	−	*	*	ND	−	*	ND	*	ND	−
	R−A1	*	ND	−	*	ND	*	−	*	ND	*	*	−	*	*	*	−	−	−	*	ND	−	*	ND	*	ND	*
	R−V2	*	ND	−	*	ND	*	−	−	ND	*	*	*	*	−	−	−	−	*	−	ND	−	−	ND	*	ND	*
	R−A2	−	ND	*	*	ND	−	−	*	ND	*	*	*	−	*	*	*	*	−	*	ND	−	*	ND	−	ND	−
	V1−V2	*	ND	−	−	ND	−	−	*	ND	*	*	−	*	*	−	−	−	−	*	ND	−	−	ND	−	ND	−

*: Significant difference −: No significant difference ND: not done $p < 0.05$

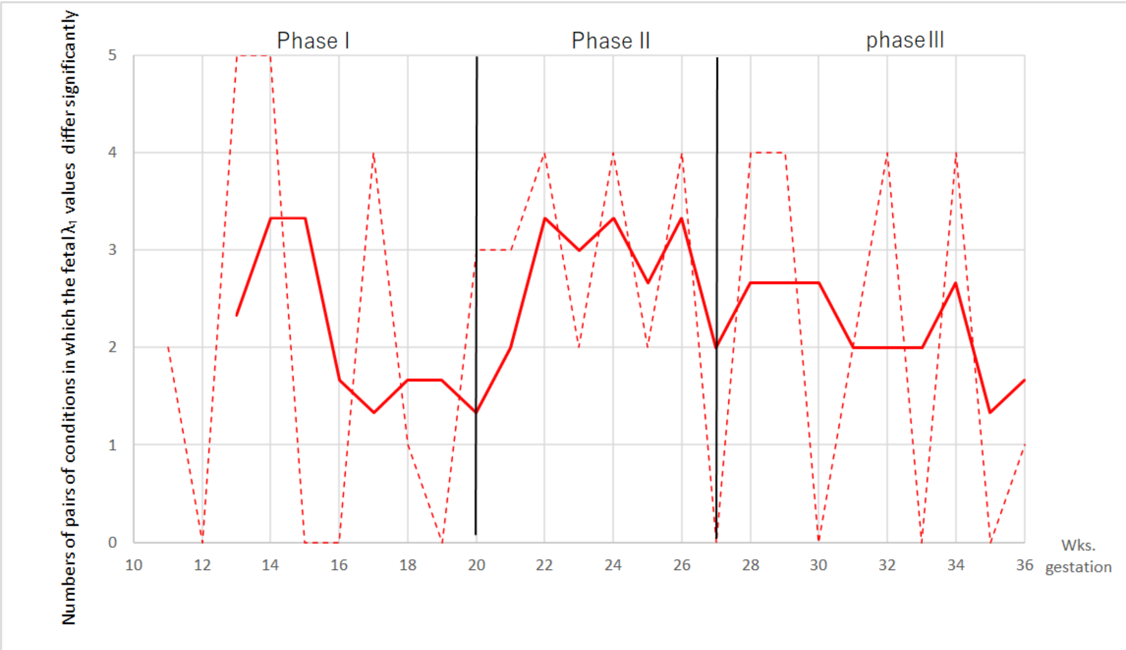

Figure 1. Numbers of pairs of conditions in which the fetal λ_1 values differ significantly and it's moving average

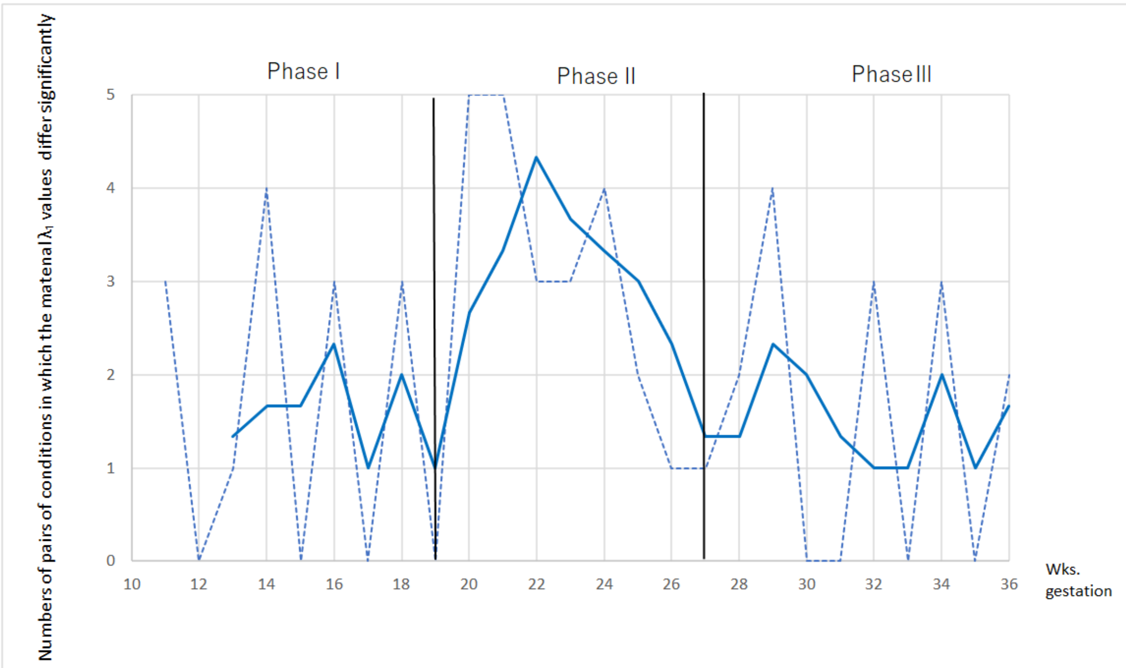

Figure 2. Numbers of pairs of conditions in which the maternal λ_1 values differ significantly and it's moving average

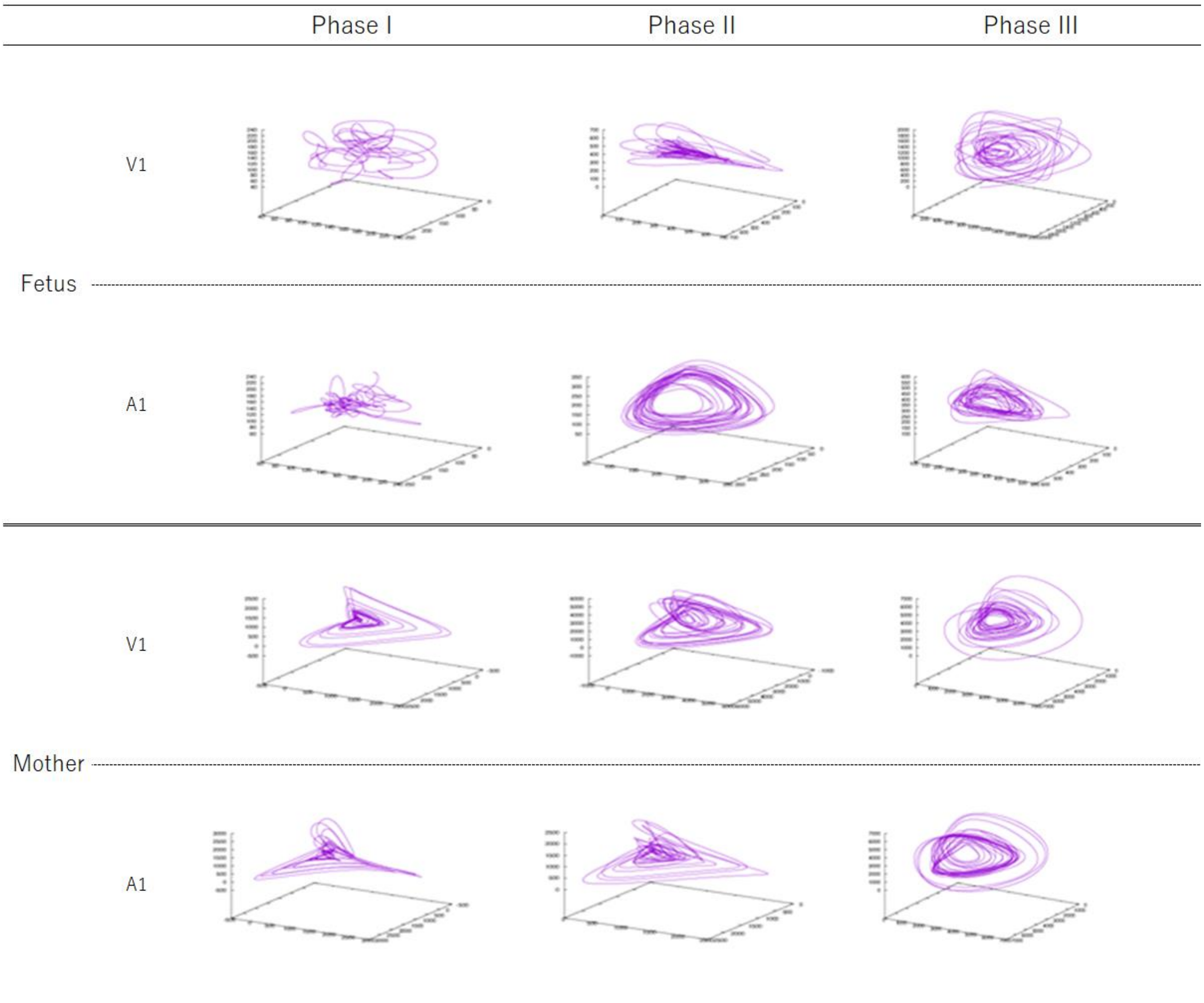

Figure 3. Attractors for while the mother's recorded voice was being heard (V1) and after the mother's recorded voice had finished being heard (A1)

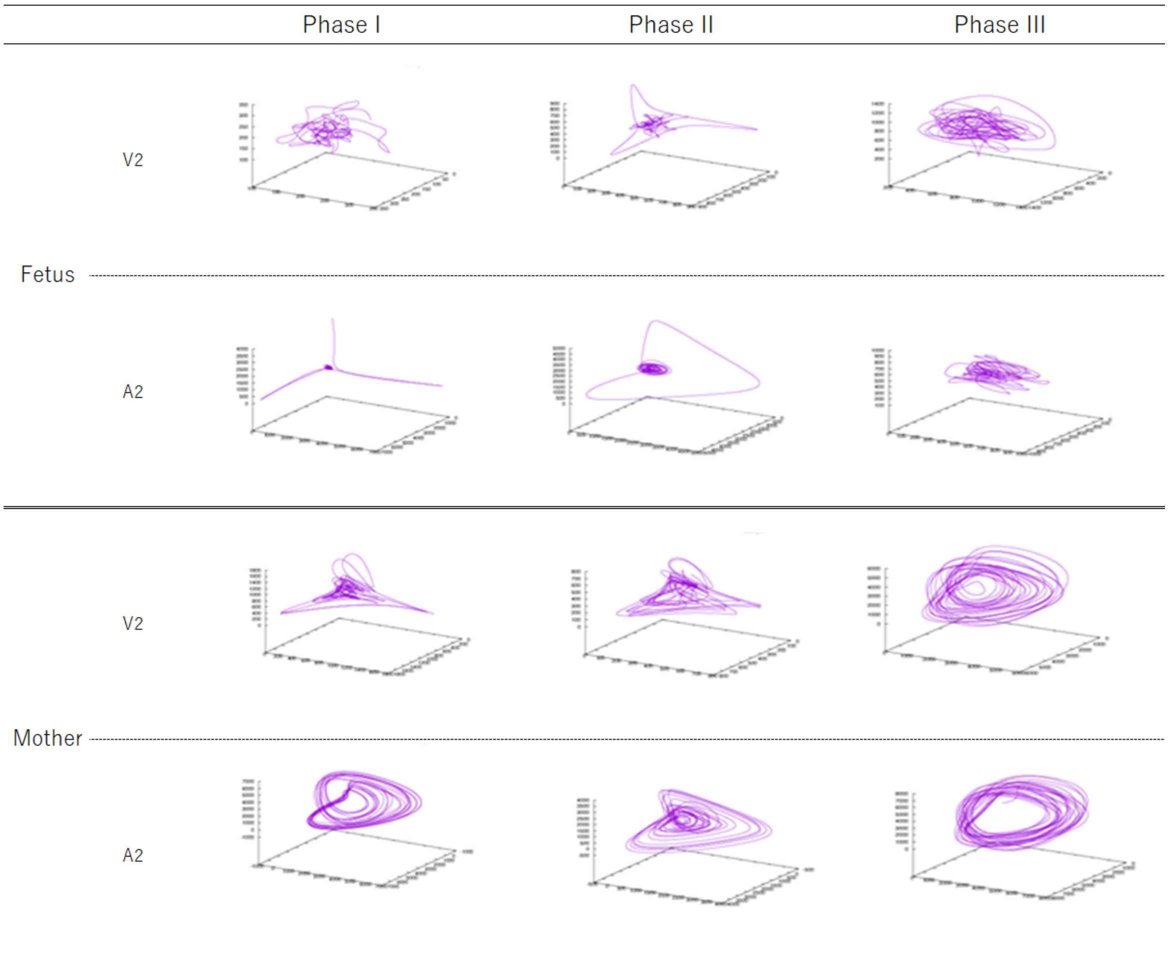

Figure 4. Attractors for while a stranger's recorded voice was being heard (V2) and after the stranger's recorded voice had finished being heard (A2)

Discussion

Emotional stimuli are processed by the amygdala of the limbic system and then integrated by the hypothalamus, that is, the center of the autonomic nervous system and the endocrine system, whose response triggers the changes in the physiological functions of the respiratory system and the circulatory system. Taking this sequence into account, we analyzed and considered changes in fetal and maternal emotional responses to vocal stimuli in terms of heart sound λ_1 and heart sound attractors.Results for ANOVA for heart sound λ_1 demonstrate that fetal emotional changes consist of three emotional phases (Fig. 1). The divisions of the three fetal emotional phases are generally consistent with developmental classifications of fetal cerebral neural networks (Innocenti & Price, 2005; Huang & Xue, 2009). During Phase I, neurons develop while the cerebral cortex and neural networks are not yet fully formed. During Phase II, cerebral cortex and neural network formation progress. During Phase III, the cerebral cortex and neural networks are adequately formed, and the brain grows in mass. This process of fetal self-organization is a consequence of neurological and physical development and growth and is conceivably expressed as emotional changes. These changes can be perceived in the three phases, and emotional changes appearance in each of these phases with transitions between phases.

Next, we will discuss attractors. As emotional phases progressed from Phase I to Phase III, fetal attractors during maternal vocal stimulus transformed from nearly structureless to nearly chaos or chaotic attractors. In addition, from Phase II onwards, fetal attractors after maternal vocal stimulus approached nearly chaos or transformed into chaotic attractors (Fig. 3). Fetal attractors in response to a stranger's voice showed little change throughout the three emotional phases (Fig. 4). In contrast, maternal attractors in response to both their own voices and a stranger's voice exhibited less change than fetal attractors and were chaotic attractors from Phase I to Phase III (Figs. 3 & 4). In addition, the similarity in the forms of fetal and maternal attractors between conditions suggests that as emotional phases change, entrainment mutually occurs in fetal and maternal attractors.The above results show that as fetal emotional phases progress from Phase I to Phase III, fetal attractors transform into chaotic attractors only in response to their mothers' voices and not in response to a stranger's voice. In contrast, irrespective of the progress of mothers' emotional states from Phase I to Phase III, maternal attractors changed little and were consistently chaotic. In other words, mothers' emotions show little qualitative change. These suggests that the mother's stable emotions may serve as a foundation for inducing emotional changes in the fetus. Furthermore, the similarity of fetal and maternal attractors suggests that entrainment occurs between the fetus and the mother, which may be evidence of emotional exchange occurs between the two.

The divisions of the above three emotional phases and the behavior of the attractors are highly consistent with clinical experience. At around 20 weeks of gestation, pregnant women who feel their fetuses moving sometimes say, "It feels just like there's something strange inside me". However, as pregnancy progresses to the third trimester, when the mother talks to her fetus, the fetus responds by kicking; such fetal responses to the mother's voice are common.

The results of the present study suggest that fetuses and their mothers experience different emotional changes as pregnancy progresses and that emotional exchange occurs between fetus and mother. Fetus and mother are a deterministic chaotic system, suggesting that these results we observed are a consequence of the fetus's and mother's self-organization ability.

Going forward, in order to examine the specific emotional changes that occur between fetus and mother in each emotional phase, we will analyze the mutual information.

Conclusion

Emotional changes in the fetus and the mother occur across three emotional phases over the course of pregnancy. The emotional phases that emerge from emotion formation are expressions of fetal and maternal self-organization ability and may serve as a foundation for the development of emotional exchange between mother and fetus.

Acknowledgments

We heartily thank Prof. Ichiro Tsuda, Chubu University Academy of Emerging Sciences; Prof. Takahiro Hirai, Ritsumeikan University Faculty of Business Administration; Prof. Takashi Yanagawa, Kurume University Biostatistics Center; and Prof. Fuziko Yamazaki, Fukuoka Jo Gakuin Nursing University for their comments and suggestions. The present study was funded by a part of Grant-in-Aid for Encouragement of Scientists in Japanese Red Cross Kyushu International College of Nursing.

References

Chaffin, D. G., Goldberg G, G. and Reed K, L, (1991),"The dimension of chaos in the fetal heart Rate", *American Journal of Obstetrics & Gynecology*. Vol 165 Issue 4 Part2, pp.1425–1429.

Grassberger, P. and Procaccia, I,. (1983a), "Characterization of strange attractors", *Physical Review Letters*.Vol 50 Issue 5, pp.346–349.

Grassberger, P. and Procaccia, I,. (1983b), "Measuring the strangeness of strange attractors". *Physica D: Nonlinear Phenomena*. Vol 9, Issue 1–2, pp.189–208.

Haken, H. (1981), "Synergetics An Introduction Nonequilibrium Phase Transitions and Self-organization in Physics, Chemistry and Biology", Springer-Verlag, Berlin Heidelberg, pp.191.

Hoh J.K., Park Y.S., Cha K.J., Oh J.E., Lee H.J., Lee G.T. and Park M.I.(2007), "Chaotic indices and canonical ensemble of heart rate patterns in small-for-gestational age fetuses". *Perinatal Medicine.*Vol 35, Issue 3, pp.210–216.

Huang H. and Xue R. (2009), "Anatomical characterization of human fetal brain development with diffusion tensor magnetic resonance imaging"*Journal of Neuroscience.*Vol 29 No 13, pp.4263–4273.

Innocenti G.M. and Price D,J.(2005), " Exuberance in the development of cortical networks". *Nature*

Reviews Neuroscience. Vol 6, pp.955–965.

Ishiyama S., Iwanaga H., Tahara T., Kiyooka Y. and Ohashi K. (2018), "Fetus and mother are a deterministic chaos: Analysis of surrogate data method". *The Society for Nursing Science and Engineering*. Vol5 No1, pp.74–79.

Kikuchi A., Shimizu T., Hayashi A., Horikoshi T., Unno N., Kozuma S. and Taketani Y. (2006), "Nonlinear analyses of heart rate variability in normal and growth-restricted fetuses". *Early Human Development*. Vol 82 Issue 4, pp.217–226.

Lorenz, E.N. (1993). "The Essence of Chaos". Seattle: University of Washington Press.

Sano, M. and Sawada, Y. (1985), "Measurement of the Lyapunov spectrum from a chaotic time series". *Physical Review Letters*. Vol 55 Issue10, pp.1082–1085.

Tsuda I., Tahara T. and Iwanaga H. (1992), "Chaotic pulsation in human capillary vessels and its dependence on mental and physical conditions". *International Journal of Bifurcation and Chaos*.Vol 2 No2, pp313–324.

Valins, S.(1996), "Cognitive effects of false heart-rate feedback", *Journal of personality and social psychology*. Vol 4 No4, pp. 400-408.