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Investigating the beat by beat phase synchronization between maternal and fetal heart rates

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***Abstract*— The development of the fetal cardiovascular system plays a crucial role in fetal health. The evolution of the relationship between fetal and maternal cardiac systems during fetal maturation is a characterizing feature for fetal cardiac development. This paper aims to evaluate this relationship by investigating the beat-to-beat synchronization between fetal and maternal heart rates and its variation at different stages of pregnancy. Synchronization epochs and phase locking patterns are analyzed at certain synchronization ratios (SRs) for three gestational age groups (16-26 weeks, 27-33 weeks, 34-40 weeks). Results show that the normalized synchronization epoch is significantly different for three age groups with the p-value of $6.72*10^{-6}$ and $2.89*10^{-4}$ at SR of 1:2 and 4:5 respectively. The variance of phase locking also shows significant difference for three groups with the p-value less than 10^{-7} at four SRs. Results also suggest that synchronization may be the force behind the increase in the maternal heart rate to maintain the fetal development and provide supplies for the fetus. Overall, the findings propose new clinical markers for evaluating the antenatal development.**

I. Introduction

Fetal Monitoring is an essential procedure during pregnancy. In particular, the monitoring of the fetal cardiovascular system is of a great importance; because the development of this system is highly related to the baby's health. The fetal cardiovascular system develops into a different physical structure compared to the adults' due to the isolation from the air. The oxygenized blood is supplied for the fetus through the umbilical cord by exchanging with the maternal blood and bypassing the respiratory system. The majority of the cardiovascular system development leads to the great interest in the relationship between the maternal and fetal cardiac function. Previous researches show that the maternal psychological conditions affect the fetal heart rate (FHR) [3]. A potential interaction relationship between the fetal and maternal cardiac systems is defined as the synchronization relationship and has been established in a few research publications. This relationship is originally caused by the interaction of a weak external force between two separate systems and analyzed between cardiac and respiratory systems known as cardiorespiratory synchronization in term of the phase relationship [6]. The phase locking principle of synchronization has also been applied to other physiological systems [2,4]. Moreover, the published analyses has demonstrated the existence of fetal and maternal surrogate and real synchronization epochs[5]. Furthermore, Ivanov has found that the coupling relationship between maternal and fetal cardiac systems is independent to maternal respiratory system[1].

The previous research results conclude the synchronization relationship as the synchronization phase which only shows the synchronization points in consistent pattern between maternal and fetal heart rate, synchronization ratio and epoch at each ratio, without further analysis of synchronization behavior.

This paper aims to illustrate the synchronization analysis between fetal and maternal cardiac systems by the synchronization ratio and phase locking patterns for different gestation periods. The paper is structured as follows. In the methods section, deriving of the synchronization relationship from ECG signal is demonstrated. The analysis results of the synchronization variable features are shown in the results section.

II. Materials and Methods

The ECG data including 40 pairs of fetal ECG (fECG) and maternal ECG (mECG) were recorded. One pair was excluded for the analysis due to the abnormal range of fHR in the overall recording. The 39 pair data were collected from 37 different subjects, considering that two of them were the repeated recordings at different gestation weeks. The fECG and mECG signals were separated from 11 abdominal ECG recordings and their corresponding demographic information was also provided. The gestation period of all subjects ranges from 16 to 40 weeks (mean±SD: 30±6.7). The duration of ECG recording is 1 minute for all data except for one subject at the gestation age of 23 weeks with a 50 second recording. The 39 data pairs were separated into the following 3 groups according to the gestation period: low gestation period (L_{gp}) group for subjects under the 26 week age containing 10 subjects, a medium gestation period (M_{gp}) group for the age between 26 and 33 weeks containing 13 subjects and the high gestation period (H_{gp}) which is for the age over 33 weeks containing 16 subjects.

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A. Analysis Variables

1) Heart Rate: The average fHR and mHR of all the subjects were statistically analyzed across the three gestation groups after locating the time point of R-peak in each ECG cycle.

2) Synchronization: The synchronization of fECG to mECG is the consistent number of fECG QRS peaks in the neighboring primary cycles which is a multiple number of mECG cycles. The duration of a primary cycle which is defined as m, is taken from 1 to 4 mECG cycles to represent both short and long intervals and the number of fECG QRS in the primary cycle is defined as n. The time position of fECG QRS is calculated as a ratio with respect to the interval of the primary cycle to build up the synchronization phase map of fECG on mECG interval. The phase of the individual fECG peak ϕ in the primary cycle is:

$$\phi(t_i) = 2\pi \frac{t_i - T_m}{T_{m+1} - T_m} + 2\pi i \qquad (1)$$

where t_i and T_j are the instants of fECG and mECG peak, i is the fECG peak number and $m \in [1,4]$.

The synchronization phase of fECG φ is:

$$\varphi = \frac{mod(\phi, 2\pi)}{2\pi} \qquad (2)$$

The synchronization is formed as parallel strips in the synchronization phase at each primary cycle and the number of strips indicates the synchronized fECG cycle. The synchronization ratio (SR) is the size of the primary cycle over the total number of fECG QRS peaks as $m{:}n$ and the high SR represents the relative fast mHR or slow fHR.

During recording, the synchronization may not be entirely continuous. Each discontinuous segment of the synchronization phase is determined as a synchronization epoch (SE); the normal consideration for SE is more than two fECG QRS peaks. The duration of SE is from the first to the last of synchronization point within the epoch regardless of the size of m as it represents the synchronization duration of fECG.

The further analysis variable from the synchronization phase is the phase locking value, which is calculated as the statistical behavior of the synchronization in two adjacent primary cycles. It is the time duration between two synchronized fECG QRS at the same order in the two primary cycles divided by n (as shown in Figure1, phase locking value is $b1 - a1$). The duration of SE is also calculated from the length of the phase locking value at each epoch. The mean and the variance of the phase locking value (U_{pl} and V_{pl}) are calculated for each epoch. The gradient of phase lock value (S_{pl}) is continuous across multiple epochs for the overall synchronization at each SR and the discontinuous epochs will not change the pattern of S_{pl} , if the phase locking value is generally steady during the entire recording.

III. Results

A. Heart Rate

The L_{gp} has the highest average fHR and it decreases slightly with the increment of mHR as the gestation age increases. The p-value of the correlation relationship of fHR

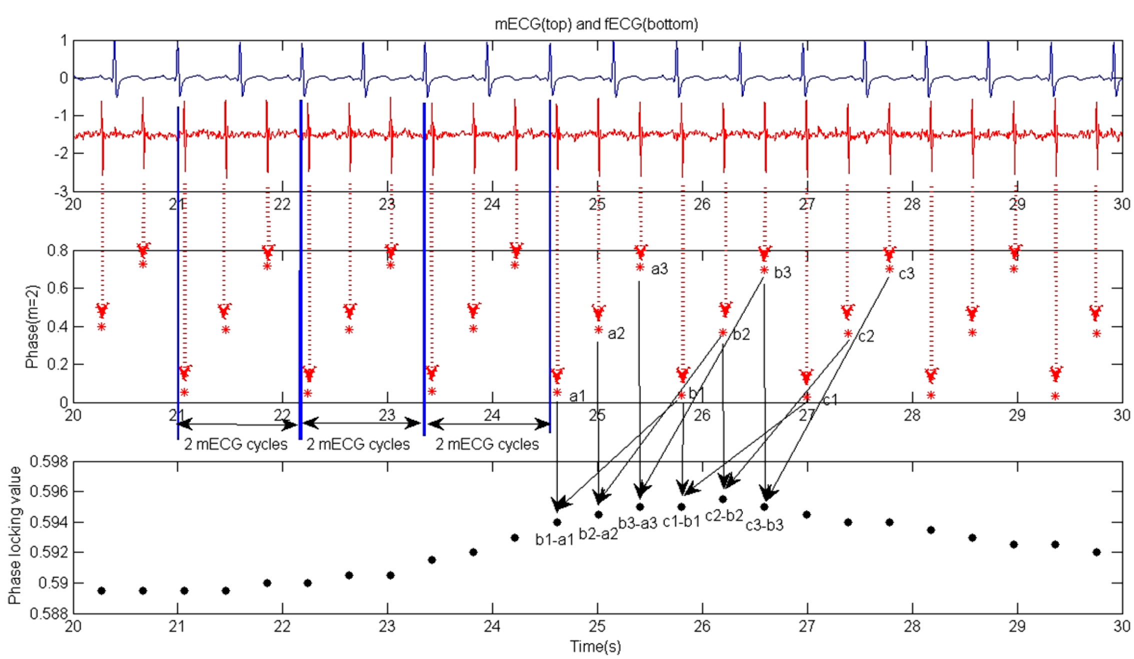

Figure 1. Top: fECG and mECG; Middle: The synchronisation points of fECG and mECG; Bottom: The phase locking value

and mHR across all three gestation groups is $p < 0.0001$. The fHR does not significantly correlate to the change of mHR at each gestation group.

TABLE I. THE MEAN AND STANDARD DEVIATION OF HEART RATE AT THREE GESTATION GROUPS

Heart Rate (beats/min)	**Gestation period**		
	L_{gp}	M_{gp}	H_{gp}
fHR Mean(±STD)	150.83±4.73	141.77± 14.33	144.76±10.68
mHR Mean(±STD)	84.49±11.13	86.91± 14.91	85.00 ±12.21

B. Synchronization

The synchronization phase is not continuous for any of the subject in the entire recording. But each subject at least has synchronization at one of the common synchronization ratios which are 1:2, 4:7, 3:5, 3:4 and 4:5. However, the ratios 3:4 and 4:5 are only for the subjects with the gestation period of M_{gp} and H_{gp} and the ratios have coupling with the increased mHR to fHR ratio. The extreme case of high synchronization ratios 4:9 exists for one subject in each gestation group and the subject in H_{gp} has the synchronization ratio up to 4:11 in the short epoch. The SEs at different SR overlap each other in time if the difference between SRs is less than 1 fECG difference in every 6 mECG cycles. Each subject can have multiple synchronization behavior during the recording and in that case multiple SRs exist in the same primary cycle. The variation of the SR in the same primary cycle indicates the reciprocal change in fHR and mHR within the 1 minute recording. The phase locking value is reciprocally related to the fHR as this value is the time duration between two fECG QRS peaks at the synchronization state and it is not affected by mHR, as shown in Figure 2.

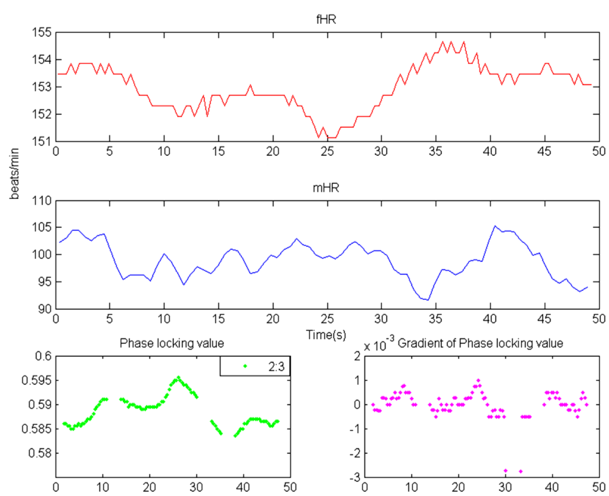

Figure 2. Top: fHR; Middle: mHR; Bottom Left: Phase locking value; Bottom Right: Gradient of Phase locking value (Spl)

The synchronization with a long primary cycle reflects the long term relationship between fECG and mECG. In that case, instant short heart rate variation may not discontinue the synchronization epoch. However it may affect the phase locking value to result in the large S_{pl} by the large variation in fHR and affect the synchronization by generating multiple short epochs in short term. On the other hand, S_{pl} may vary within an individual epoch and the different ranges of the phase locking values can result the same variance. The phase locking values overlap in time for the same SR at different primary cycles or for the different SR depending on the S_{pl}, in which condition the high S_{pl} reduces the overlapping time.

TABLE II. THE P-VALUE OF STATISTICAL PROPERTY OF SYNCHRONISATION BEHAVIOUR AT 6 MAJOR SR BETWEEN THE THREE GESTATION GROUPS

	1:2	*4:7*	*3:5*	*2:3*	*3:4*	*4:5*
Synchronization epoch (SE)	0.11	0.3706	0.11	0.23	0.75	0.18
Normliased Synchronization epoch (nSE)	6.72 * 10^{-6}	0.1923	0.0154	0.0167	0.8863	2.89* 10^{-4}
Mean value of phase locking value (U_{pl})	0.04	0.15	0.11	0.23	0.59	0.17
Variance of phase locking value (V_{pl})	3.68* 10^{-12}	0.09	7.43* 10^{-8}	1.07* 10^{-9}	0.37	4.98* 10^{-12}
Gradient of phase locking value(S_{pl})	0.90	0.27	0.77	0.44	0.88	0.97

The normalized synchronization epoch (nSE) of L_{gp} is relatively high for SR between 1:2 and 3:5 and it drops with the decrease in SR. Inversely, nSE increases with the decrease in SR and reaches the dominant condition at 2:3 for H_{gp}. It shows that the dominant SR for L_{gp} is relatively high compared to H_{gp} and M_{gp}, which represents the transient condition for reduction of synchronization ratio.

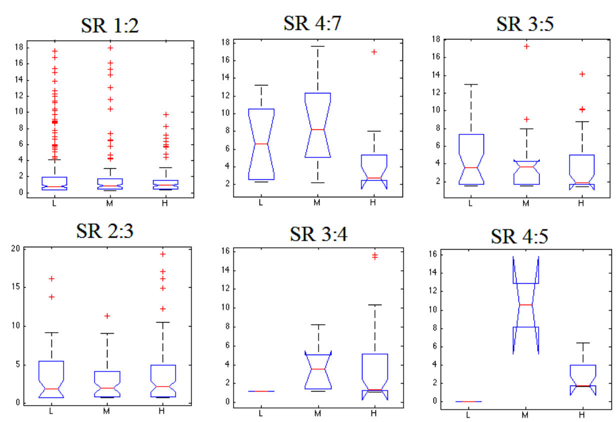

Figure 3. The mean and standard deviation of normalized synchronization epoch at major synchronization ratios(1:2, 4:7, 3:5, 2:3, 3:4 and 4:5)

The general statistical parameters including mean and standard deviation of the normalized synchronization epoch were compared for three gestation groups at individual major synchronization ratio as shown in Figure 3. For the subject with the recorded signal at the age of 27 and 28 weeks, SR is consistent, as it is 1:2 at the two gestation ages. The correlation between the fHR of the two gestation periods is -0.22 and for mHR, it is 0.27. They still form the same synchronization relationship in similar duration. Both recordings are considered in M_{gp} group and there is no change in synchronization behavior.

IV. Discussion

Different from the cardiorespiratory synchronization, the synchronization relationship between fetal and maternal cardiac systems is taken from the pairs of signals originated from the same function of two biological individuals. Therefore instead of neural connection between cardiovascular and respiratory system, there is a physical connection with oxygen supply between fetus and mother which demonstrates the interconnection of the oxygen level and FHR.

In our experiment, the number of subjects in each gestation group is not consistent and the highest gestation period has the largest number of subjects. The subjects in each gestation period are not identical and each subject may have various heart rate features at different gestation periods. Thus the synchronization behavior at different gestation stage may not link the gestation period to the heart rate change correspondingly.

In most cases, multiple SEs occur in each primary cycle due to heart rate variations, but the duration of SEs is not consistent for the same SR. The increased variance of S_{pl} reflects the possibility of losing synchronization at the corresponding synchronization ratio. Assuming the synchronization relationship with a certain ratio to the mECG cycle, the variance of S_{pl} may indicate a complex development of the fetus which disrupts the steady synchronization to the maternal cardiac system. The shortage of oxygen supply from mother may alter both systems. Also, the synchronization relation is strong at the early stage of gestation and stays in a reasonable ratio between 2:3 and 1:2 for the stable oxygen supply. The synchronization may be the force behind the increased mHR to maintain the fetal development and to keep with nutrient requirement. The increased mHR raises the circulation of blood exchange at placenta for the same fHR and SR represents the blood exchange rate.

V. Conclusion

The synchronization relationship between fetal and maternal cardiac systems shows different features in terms of synchronization ratio and epoch within three gestation periods between 16 and 40 weeks. The subjects are separated into three gestation groups without even number of subjects across the groups. Some subjects have overlapped synchronization features as they are not recorded consistently for the same subjects in each group. The synchronization analysis demonstrates the potential inter-correlation between the mother and the fetus through the oxygen supply which can also be applied as separation indication for different gestational stages.

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