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Cardiorespiratory phase synchronization during normal rest and inward-attention meditation

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The interaction between human cardiac and respiratory systems has been widely studied for many decades. One well-known phenomenon of cardiorespiratory interaction is respiratory sinus arrhythmia (RSA) [1]. Besides RSA, another cardiorespiratory interaction, cardiorespiratory phase synchronization (CRPS) [2], has recently been studied. CRPS may establish an effectual co-action between cardiac and respiratory systems which can preserve the body energy [3,4]. Compared with RSA being stable even under cognitive arousal, CRPS was most visible under conditions of low cognitive activity, such as during sleep [4,5] and anesthesia [6,7], and was almost lost during physical strain [4]. The effects of various meditation techniques on RSA have been examined [8–10]. This study mainly explored the CRPS during normal rest and inward-attention meditation.

Two groups of subjects were recruited in this study. The experimental group comprised seven experienced Chan-meditation practitioners (2 females and 5 males; mean age 26.4±2.5 years; mean meditation experience 5.9±2.6 years); the control group comprised nine non-meditators (one female and eight males; mean age 25.3±3.3 years). All subjects were free of cardiac, pulmonary, and other chronic diseases. Also, none of the subjects were smokers or consumers of caffeinated alcoholic drinks. Each subject provided written informed consent (in accordance with the Helsinki Declaration) to the study.

The experiments comprised two sessions. During Session 1, both groups of subjects rested, in a ~70° head-up back-tilt position with their eyes closed, for 10 min. During Session 2, control subjects continued resting for 20 min; meanwhile, experimental subjects meditated for 20 min. Experimental subjects, according to their routine, meditated in either a full or half lotus posture, with eyes closed. During meditation, practitioners concentrated their mind on “Chan Chakra”, located inside the third ventricle of the brain. All subjects breathed spontaneously during both sessions.

The electrocardiogram (ECG) and respiration signals were recorded simultaneously at 1000 Hz using the PowerLab/16SP recording system (ADInstruments, Sydney, Australia). The ECG signal was recorded using Lead I of standard bipolar limb leads, and the respiratory signal was recorded using a piezo-electric transducer (Model 1132 Pneumotrace II (R), UFI, Morro Bay, CA, USA) wrapped around the belly passing the navel.

This study used the synchrogram method to analyze the CRPS. The *normalized relative phases* (see Appendix A) of heartbeats within *m* respiratory cycles were calculated and plotted against the times of heartbeats (t_k, the occurrence of

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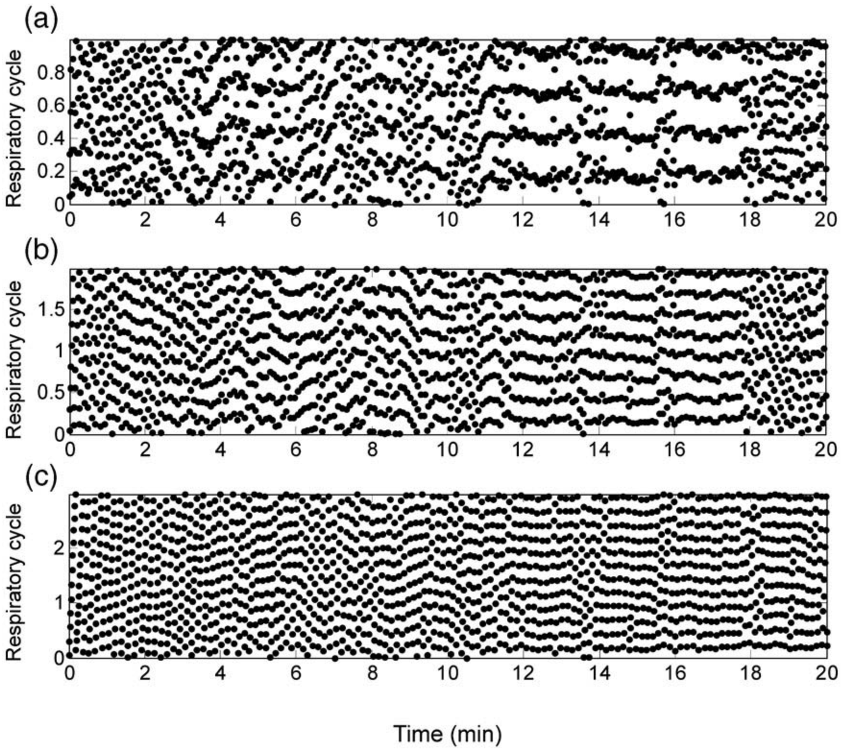

Fig. 1. The synchrograms of experimental subject 1003 during meditation: (a) *n*:1 synchrogram (b) *n*:2 synchrogram (c) *n*:3 synchrogram. The 4:1 synchronization is evidently observed at 11–18 min, showing four horizontal lines in the *n*:1 synchrogram.

R peaks) to construct the synchrogram. This study observed the CRPS within three respiratory cycles. Three synchrograms with $m = 1$, 2, and 3 thus were plotted for each subject (see Fig. 1).

For the case of n:m synchronization, n heartbeats are encompassed within the period covering m cycles of respirations, and will result in n horizontal lines in the synchrogram (see Fig. 1(a)). Consequently, synchronization

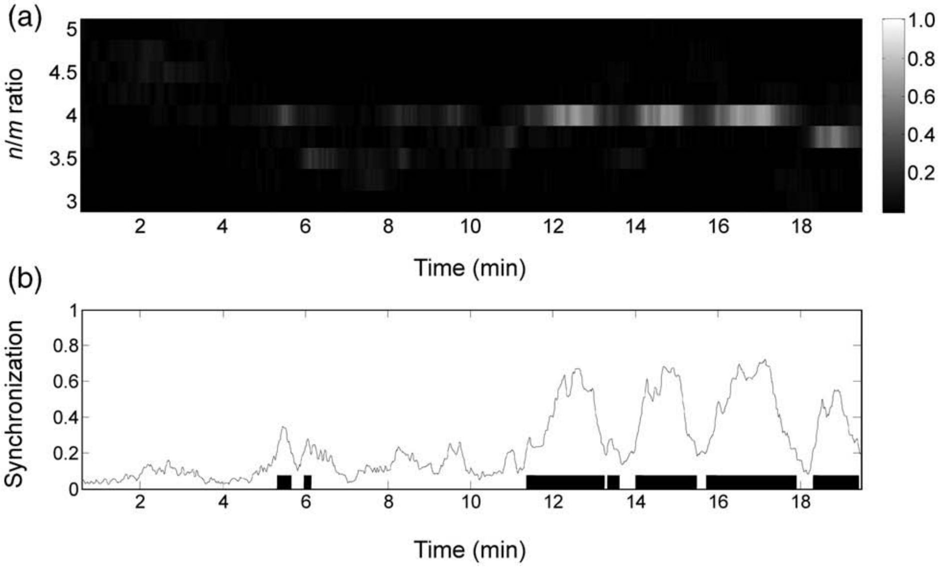

Fig. 2. Synchronization degree of experimental subject 1003 during meditation: (a) Time-varying synchronization degrees $\gamma_{n,m}(t_k)$ for all possible (n,m) pairs. The right color bar denotes the scale mapping for color representation. The map clearly illustrates the transition of synchronization between different *n/m* ratios and the corresponding synchronization degrees. (b) Time-varying characteristic synchronization degree $\gamma_{\max}(t_k)$ of (a). For each time t_k, the value of $\gamma_{\max}(t_k)$ is determined by the maximum value of $\gamma_{n,m}(t_k)$ across all possible (n,m) pairs. The black bars on the bottom illustrate the significant synchronization epochs with synchronization degrees exceeding 0.2 and durations exceeding 10 s.

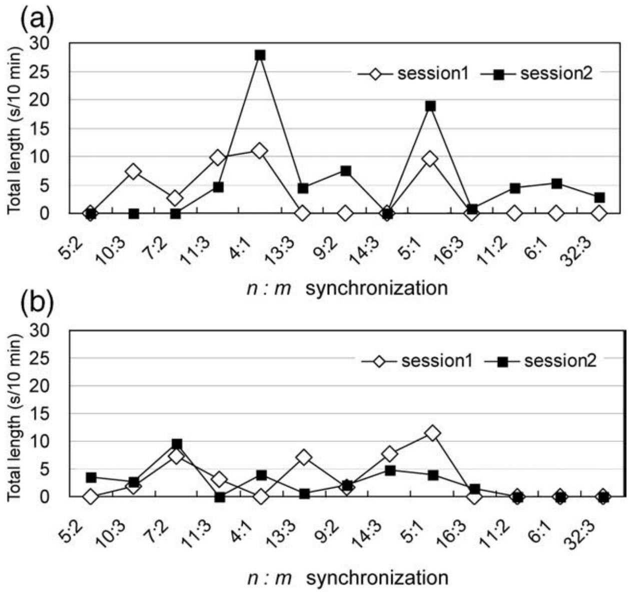

Fig. 3. The average total length of significant synchronization epochs at different n:m for (a) the experimental group and (b) the control group.

degree can be quantified by characterizing the distribution of the normalized relative phase values of heartbeats (see Appendix A). Fig. 2(a) illustrates the time-varying synchronization degrees $Yn,m(t_k)$ of an experimental subject during meditation for all possible (n,m) pairs. For each time t_k, the maximum value of $\gamma_{n,m}(t_k)$ across all possible (n,m) pairs was then applied as the *characteristic synchronization degree*, and the resulted sequence was denoted by $Ymax(t_k)$. Fig. 2(b) shows the sequence $\gamma_{\max}(t_k)$ extracted from $\gamma_{n,m}(t_k)$ of Fig. 2(a).

To identify the periods of significant synchronization in a relative sense, we set a threshold α (=0.2) and looked up for the continuous period within which synchronization degrees exceeded α. A continuous period with duration longer than 10 s (approximately 2–3 respiration cycles) was considered as a *significant synchronization epoch*.

The frequency ratio and three synchronization parameters (lasting length, number of epochs, and total length) were measured in this study. We defined the lasting length, number of epochs, and total length as follows:

1. Lasting length (s/epoch): Duration of a significant synchronization epoch;
2. Number of epochs (counts/10 min): Number of significant synchronization epochs per 10 min;
3. Total length (s/10 min): Total durations of all significant synchronization epochs in 10 min.

Fig. 3 shows the average total length of significant synchronization epochs at different n:m for both groups. Apparently, frequency ratio below 5 was dominated for both groups and both sessions. Additionally, the experimental subjects during meditation showed a predominance of 4:1 and 5:1 synchronizations.

As shown in Table 1, two-way ANOVA analysis revealed neither significant main effect (group or session) nor significant interaction effect (group × session) for the frequency ratio and lasting length of synchronization, but revealed significant interaction effects for number of epochs [$F(1,14)=7.30$, $p=0.017$] and total length [$F(1,14)=4.67$, $p=0.048$]. Further test of simple effects revealed a significant increase in number of epochs [$F(1,14)=6.45$, $p=0.024$] and total length [$F(1,14)=5.49$, $p=0.034$] for experimental subjects from Session 1 to 2, but no significant difference for the control subjects.

In this study, a predominance of 4:1 and 5:1 synchronizations was observed in experimental subjects during meditation. In an earlier paper [11], similar predominance was reported under the state of non-REM sleep, primarily on 4:1 synchronization. Moreover, Stefanovska *et al.* [6] observed that the frequency ratio of CRPS exhibited the transition 2:1 → 3:1 → 4:1 → 5:1 as anesthesia depth increased. This may indicate that the frequency ratio of CRPS is related to the states of consciousness, and the 4:1 and 5:1 synchronizations are the ones correlating with low cognitive activity.

According to the statistical analysis, for the experimental group, number of synchronous epochs and the total synchronization length increased considerably during meditation. Notably, the lasting length of synchronization did not

Table 1
The values of frequency ratio and three synchronization parameters for the control and experimental groups during two experimental sessions.

	Control group ($n=9$)		Experimental group ($n=7$)		p-Value		
	Session 1 (baseline)	Session 2 (rest)	Session 1 (baseline)	Session 2 (meditation)	Group effect	Session effect	Interaction effect
Frequency ratio (f_h/f_r)	4.2±0.8	4.0±0.7	4.5±0.9	4.9±0.8	NS	NS	NS
Lasting length (s/epoch)	21.3±10.7	24.9±9.5	27.0±16.6	30.0±16.5	NS	NS	NS
Number of epochs (counts/10 min)	1.8±1.1	1.4±0.5	1.4±1.1	2.4±1.0	NS	NS	0.017*
Total length (s/10 min)	41.1±25.2	32.6±10.5	40.7±26.1	77.7±69.5	NS	NS	0.048*

Values are means ± SD. NS = not significant; *Significant difference ($p<0.05$). The f_h and f_r denote the instantaneous frequencies of heart beat and respiration, respectively.

differ significantly during meditation. The increase in total synchronization length is thus due to the increased number of synchronous epochs. On the other hand, the control group exhibited no significant difference between the two sessions in all the three synchronization parameters. This study thus concludes that meditation, compared with normal relaxation, can cause more frequent CRPS.

In conclusion, this study has demonstrated that besides RSA, phase synchronization is another type of cardiorespiratory interaction that can be enhanced during meditation. The increase of CRPS during meditation provides further evidence that CRPS is best observed in conditions of low cognitive activity.

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Appendix A

Normalized relative phase

The normalized relative phases of heartbeats within m respiratory cycles are defined as

$$\psi_m(t_k) = \frac{1}{2\pi}[\phi_r(t_k)\mathrm{mod}(2\pi m)] \tag{A1}$$

where $\phi_r(\cdot)$ is the instantaneous phase of respiration signal, and t_k is the time of the kth heartbeat, which is determined by the R peak. The operation 'mod $(2\pi m)$' denotes wrapping the phase values into the interval $[0,2\pi m)$ (i.e. m consecutive respiratory cycles are integrated into one longer cycle).

Quantification of synchronization

Since a high degree of n:m synchronization introduces n horizontal lines in the synchrogram, quantification can be achieved by examining the regularity of the normalized relative phase $\psi_m(t_k)$ in the synchrogram. Based on this concept, this study first transforms $\psi_m(t_k)$ to $\Psi_{n,m}(t_k)$ using the equation

$$\Psi_{n,m}(t_k) = \frac{2\pi}{m}\{[\psi_m(t_k)\cdot n]\mathrm{mod}\ m\}. \tag{A2}$$

Based on Eq. (A2), the n horizontal lines are merged into one horizontal line. The degree of n:m synchronization, $\gamma_{n,m}$, can then be assessed by measuring the invariance of $\Psi_{n,m}(t_k)$ following the equation below

$$\gamma_{n,m} = \left\{\frac{1}{N}\sum_k \cos\left[\Psi_{n,m}(t_k)\right]\right\}^2 + \left\{\frac{1}{N}\sum_k \sin\left[\Psi_{n,m}(t_k)\right]\right\}^2, \tag{A3}$$

where N represents the number of heartbeats in a given window length. The value of $\gamma_{n,m}$ ranges from 0 to 1, with $\gamma_{n,m}=1$ ($\gamma_{n,m}=0$) denoting *complete synchronization* (*complete desynchronization*).

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