國立交通大學
電機與控制工程學系

博士論文

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研究生：吳適達

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研究生：吳適達　　Student：Shr-Da Wu
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摘　要

本論文主要研究禪坐的解壓機制。研究分為心理和生理因素，以兩組受測者（有禪坐經驗和沒有禪坐經驗）為研究對象。

在心理因素方面，本論文採用問卷調查的方式，以 DASS 量表來評估受測者的負面情緒狀態（沮喪 depression、焦慮 anxiety 和緊張 stress／tension）。受測者分為兩個族群：日常生活中有禪坐練習和沒有禪坐練習的大學生。研究結果顯示，比起一般的大學生（無禪坐的族群），有禪坐習慣的大學生中有負面情緒問題的比例較低。研究中還探討了禪坐經驗、禪坐時間和禪坐次數這幾個因素對負面情緒的效應。其中發現，對於沮喪和焦慮，禪坐經驗（半年以上）是有效改善這兩種負面情緒的重要因素。

在生理因素方面，本論文主要探討心率變異（heart rate variability, HRV）和心肺相位同步（cardiorespiratory phase synchronization, CRPS）兩種生理現象。其中，心率變異已在臨床和研究中被廣泛用來了解自主神經的功能，本論文中針對心率變異的時域和頻域特性進行分析。結果顯示禪坐中 LF/HF ratio 和 LF norm 的數值下降，而 HF norm 的數值上升，表示禪坐能使自主神經的交感／副交感平衡趨向於副交感神經的活動。此外還發現，在禪坐中處於低 LF/HF ratio 時，心率變異會呈現規律的律動。

心肺相位同步是近期被研究的一種心肺交互作用，被認為可能反應心肺系統間處於高效能的協同運作狀態，可以減少能量的消耗。本論文中以同步觀測圖法（synchrogram）來檢測心肺相位同步現象。我們針對心電圖（ECG）和呼吸訊號進行分析，並定義三個量化參數（每次同步持續的時間長度、同步的次數、同步的時間總長度）來探討禪坐對

心肺相位同步的影響。結果顯示，禪坐中心肺相位同步的次數和時間總長度明顯增加；此外，禪坐中的心肺相位同步現象會呈現 4:1 和 5:1 兩種主要的頻率比。

Study of Chan-Meditation Mechanisms for Stress Manipulation

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Abstract

This dissertation is aimed to investigate the mechanisms of Chan meditation for stress manipulation. The study involving both the psychological and physiological factors was conducted for two groups of subjects who with and without Chan-meditation experience.

In the psychological-factor study, a survey study was conducted by evaluating the negative emotional states of college students with and without Chan-meditation practice in their daily lives. The DASS questionnaire was used to measure the negative emotional states (depression, anxiety and stress/tension). The results showed that, compared with non-practitioners, much lower percentage of college students with routine Chan-meditation practice had negative-emotion problems. Other factors including experience, duration and frequency of Chan meditation are also investigated and reported in the dissertation. One significant finding suggests that meditation experience (>0.5year) is essential for effective management of depression and anxiety.

In the physiological-factor study, we focused on the behaviors of heart rate variability (HRV) and cardiorespiratory phase synchronization (CRPS), based on the designed experimental protocols. HRV has being extensively employed in understanding the function of autonomic nervous system both in clinics and researches. We analyzed the HRV both in time and frequency domains. The major effects of meditation on HRV were the decrease of

LF/HF ratio and LF norm as well as the increase of HF norm, which suggested the benefit of a sympathovagal balance toward parasympathetic activity. Moreover, we observed regular oscillating rhythms of the heart rate when the LF/HF ratio was small under Chan meditation.

CRPS was applied to the study of cardiorespiratory interactions most recently. It may establish an effectual co-action between cardiac and respiratory systems for better preservation of bodily energy. This dissertation presents the approach of synchrogram analysis for studying the CRPS. In the synchrogram scheme, we first evaluated phase synchronization between cardiac and respiratory systems by analyzing electrocardiogram (ECG) and respiration signals. In addition, three synchronization parameters (lasting length, number of epochs, and total length) were defined to examine the efficacy of Chan meditation in the cardiorespiratory phase synchronization. Statistical analysis reveals that the number of synchronous epochs and the total synchronization length significantly increase during Chan meditation. Furthermore, a predominance of 4:1 and 5:1 rhythm-ratio synchronizations was observed during Chan meditation.

誌　謝

漫長的學生生涯終於要告一段落了！

會繼續攻讀博士，就只因為大一時對科學研究的一份憧憬，從未想到會有如此艱辛的過程。要不是有許多貴人的幫助和支持，怎麼可能完成這個單純的夢想。

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Chapter 1 — Introduction

As the society progresses rapidly, stress has become an increasingly important matter of modern life. Many physical and psychological problems in modern people have been proven to be caused by stress. This finding stimulated the demand for techniques (stress management interventions) that can effectively manipulate the stress perception.

Meditation, as the category of *mind-body intervention* in CAM (complementary and alternative medicine, see Appendix A), has been extensively studied since the 1960s and been proved to benefit human health in various aspects (Kabat-Zinn *et al.* 1985; Sudsuang *et al.* 1991; Wenneberg *et al.* 1997; Shapiro *et al.* 1998; Davidson *et al.* 2003; Lazar *et al.* 2005; Liu *et al.* 2007; Tang *et al.* 2007). Our research group has been investigating the meditation since 1998. In the beginning, we attended to the brain dynamics during meditation and most studies were hence based on electroencephalograph (EEG) signals. In recent years, due to the issue of stress, we also devoted to the effects of meditation on stress release.

1.1 Background

Stress management interventions are defined as any procedures designed to enhance the ability of people to cope with stressors or with the negative emotions elicited by them (Auerbach and Gramling 1998). According to Lazarus and Folkman's (1984) appraisal model, interventions for stress management can be categorized into three types: problem-focused, emotion-focused, and mixed (both problem-focused and emotion-focused) interventions. The problem-focused techniques attempt to cope with the stressors; the emotion-focused techniques attempt to moderate people's emotions; and the mixed techniques manage the stress on both ways. Table 1-1 lists the examples for each category of stress management interventions. In the branch of emotion-focused techniques, the mind-body intervention in CAM plays an important role.

Table 1-1. Categories of stress management interventions

Category	Stress Management Interventions
Problem-focused	Social Skills Training (ex. Time Management, Assertiveness Training)
Emotion-focused (Mind-Body Interventions)	Progressive Muscle Relaxation Autogenic Training Meditation Yoga Biofeedback Music Therapy
Mixed	Cognitive-Behavioral Approaches

The concept that mind (thoughts and emotions) can affect our body originated from the traditional medicine of Chinese and Indian more than 2000 years ago. In the 1930s, Canon's (1929, 1932) studies on stress response firstly provided the scientific evidence for the mind-body interaction. He found that psychological stress can induce increased activity of sympathetic nervous system, central nervous system, and skeletal muscle. Later in 1936, Selye's study on neuroendocrine effects of stress response firstly provided the evidence for stress-disease linkage. He recognized stress as a process involving three phases: alarm, resistance, and exhaustion phases. He found when the stress extended to the third phase (exhaustion phase), it will result in illness such as ulcer. In 1957, Hess observed a physiological response counterbalancing to stress response revealing as reduced sympathetic nervous, central nervous system, and skeletal muscle activities. Such response was later named as “relaxation response” and suggested as a common response for all mind-body interventions by Benson *et al.* (1974).

Because stress is a phenomenon of mind-body interaction, the effectiveness of stress management can be studied on psychological and/or physiological aspects. For the psychological aspects, the perceived stress of participants can be measured by questionnaires. For the physiological aspects, three body systems (cardiovascular, neuroendocrine, and immune systems) that are mainly involved in the stress response can be considered. The neuroendocrine system includes the nerves system (mainly the central nerves system (CNS) and autonomic nervous system (ANS)) and the endocrine system. In this dissertation, the perceived stress and two physiological phenomena related to nerves and cardiovascular systems are studied.

1.2 Aims of this work

The main aim of this dissertation is to investigate how Chan meditation manipulates the human stress. To attain this aim, both the psychological and physiological factors were studied and compared between two groups of subjects who with and without meditation experience.

In the psychological aspects, a survey study was conducted by evaluating the negative emotional states of college students with and without Chan meditation practice in their daily lives. And the following questions were examined: (1) how is the negative emotional states of college students in Taiwan? (2) to which degree the experimental subjects (students who practice Chan meditation) can handle their negative emotional states in comparison with the control subjects? (3) how the meditation experience, duration, and frequency affect the ability of stress manipulation?

As regards the physiological factors, we focused on two physiological phenomena namely heart rate variability (HRV) and cardiorespiratory phase synchronization (CRPS). A laboratory-controlled experiment was designed and carried out for the physiological studies. Among various meditation techniques, our experiment mainly explored the effects of inward-attention meditation. Inward attention has been an important approach for Chan practitioners to enter into transcendental consciousness. Practitioners concentrate their mind on a specific chakra (an energy spot inside the body) to release themselves from wild and uncontrollable thoughts and enter a transcendental-consciousness state. Such state during meditation may benefit stress release.

HRV has being extensively conducted to explore the autonomic function both in clinical and laboratory research. A number of literatures have reported the effects of meditation on heart rate variability (Lehrer *et al.* 1999; Peng *et al.* 1999; Peng *et al.* 2004; Cysarz and Büssing 2005; Takahashi *et al.* 2005). However, most studies have been focused on the skill of slow breathing. In 1999, Peng *et al.* observed very prominent low-frequency (~0.1Hz) RSA in heart rate during specific forms of Chinese Chi and Kundalini yoga meditation. In their later study (2004), same phenomenon was also observed in two forms of meditation with different respiration techniques. In 2005, Cysarz and Büssing observed prominent in-phase RSA, caused by low-frequency breathing, during Zazen meditation and Kinhin meditation. These studies showed that meditation techniques characterized by slow breathing (<0.15 Hz, less than 9 breaths in one minute) could result in very prominent and regular oscillations in the LF band of HRV. Our study focused on the technique of inward attention and mainly explored its effects on ANS.

CRPS is a recently investigated phenomenon reflecting certain type of interaction between cardiac and respiratory systems. According to previous studies (Raschke 1991; Toledo *et al.* 2002), cardiorespiratory phase synchronization may establish an effectual co-action between cardiac and respiratory systems which can preserve the body energy. Cardiorespiratory phase synchronization was most visible under conditions of low cognitive activity, such as during sleep (Bartsch *et al.* 2007; Raschke 1991) and anesthesia (Galletly and Larsen 1997; Stefanovska *et al.* 2000), and was almost lost during physical strain (Raschke 1991). The transcendental-consciousness state during meditation is a condition of low cognition level. According to previous studies, it may facilitate the appearance of CRPS.

1.3 Organization of this dissertation

This dissertation is composed of five chapters. Figure 1-1 illustrates the hierarchy associating different chapters.

In the beginning, Chapter 1 introduces the background and the aims of this research. To investigate the meditation effects on stress manipulation in psychological aspects, Chapter 2 presents our survey study administrating questionnaires to evaluate the perceived stress (depression, anxiety and stress/tension) of a large pool of college students. How meditation practice affects the perceived stress was examined by comparing the three psychological factors between college students with and without meditation practice in their daily lives.

In the physiological aspects, Chapter 3 focuses on the heart rate variability which can reflect the autonomic function. A laboratory-controlled experiment was designed and carried out. The heart rate variability was analyzed both in time and frequency domains and compared between experimental and control groups. In Chapter 4, we explored the cardiorespiratory phase synchronization which may be an indicator of good coordination between cardiac and respiratory systems. The synchrogram scheme and corresponding quantification method for measuring synchronization degree are introduced. Three synchronization parameters were defined to examine how meditation affects the cardiorespiratory phase synchronization.

The last chapter discusses the results and summarizes the findings of this study. This chapter concludes with our anticipation of future work.

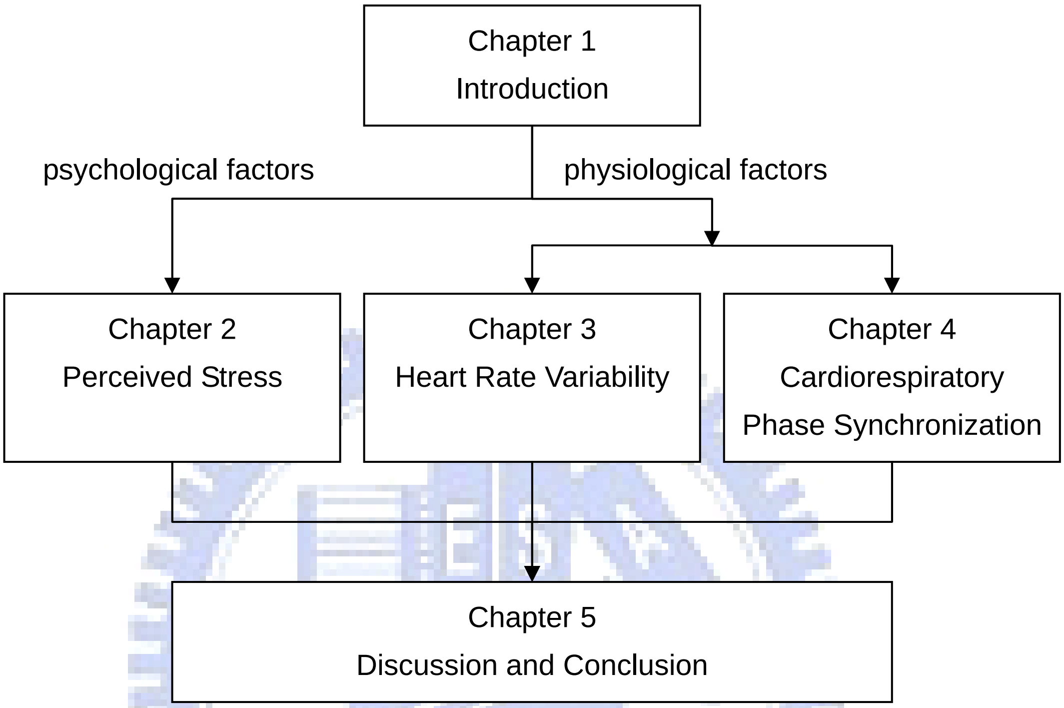


Figure 1-1. Chapter hierarchical structure.

Chapter 2 –

Investigation of Meditation Effects on Perceived Stress

The effectiveness of short-term meditation practice on stress management has been proved in different groups of subjects including students, teachers, patients, etc. In the study of Shapiro *et al.* (1998), premedical students accepted an eight-week meditation-based stress-reduction intervention could effectively reduce anxiety and depression levels as well as increase empathy level and spiritual experiences. Winzelberg and Luskin (1999) reported that a four-week meditation training for the secondary-school teachers could effectively reduce their certain manifestations of stress except for anxiety. The study of Majumdar *et al.* (2002) showed that an eight-week mindfulness meditation program could effectively reduce psychological distress and increase well-being and quality of life for participants with chronic physical, psychological, or psychosomatic illness.

Our study focused on the group of college students and extended to investigate the effects of long-term meditation practice. This survey study thus focuses on the group of college students and mainly examines the effects of Chan-meditation practice on their perceived stress. Our survey involved two groups of participants, totally 541 college students. Experimental/control group included subjects with/without Chan-meditation practice in their daily lives. To evaluate the perceived stress of participants, DASS questionnaire was used to measure their negative emotional states.

2.1 Stress problems of college students

In an annual survey report, Leo (2000) found that increasing numbers of college students were reported to feel overwhelmed and stressful. This indicates that stress becomes a more and more important issue on college campuses. The stress of college students was primarily related to academic, personal, and negative life events (Archer and Lamnin 1985; Li and Lin 2005). This general pattern of stress-producing incidents has remained relatively constant over the past 15 years in American college students (Murphy and Archer 1996). Students may need a certain level of stress to improve their performance. However, excess stress will negatively affect health, personality, and even academic performance. Especially, the level of stress experienced by college students has been documented as a predictor of suicidal ideation and hopelessness (Dixon *et al.* 1992). Hence, an effective method for college students to manage their stress in daily lives is valuable. Since college students are at the age of fast development of personality and life viewpoint, the stress may cause long-term, substantial effects on future life.

2.2 Survey study

2.2.1 Participants

Participants of this study involved 541 students from four universities (National Taiwan University, National Tsing Hua University, National Chiao Tung University and Chung Yuan Christian University) in Taiwan. The participants in the experimental group were the students with Chan-meditation experience. The participants in the control group were the students without any meditation experience. Their information is listed in Table 2-1.

Table 2-1. Participant information for experimental group and control group

	Control Group	Experimental Group
Number of participants	456	85
Sex (male : female)	350 : 106	57 : 28
Age (Mean ± SD years)	22.7 ± 2.3	23.1 ± 2.8
Education degree (under-graduates : graduates)	327 : 129	54 : 31

2.2.2 Intervention

The experimental-group participants all have learned the Chan-Buddhist meditation (see Appendix B) in the Chan club of their university. They attended a 90-minute weekly Chan-meditation program over an 8-week period, and afterwards continue the meditation practice in their daily life. In the Chan-Buddhist meditation, meditators sit in the full-lotus, half lotus, or free-style position with eyes closed. Two major techniques for a beginner to get into good-quality meditation are: (1) switching the breathing habit from chest to abdominal breathing so that the breathing becomes smoother, deeper, and quieter, and (2) focusing on some important spots like the Chan Chakra (inside the third ventricle), the Wisdom Chakra (corpora quadrigemina), or the Dharma-eye Chakra (hypophysis). They normally concentrate their mind on particular Chakra(s) in the beginning to release themselves from uncontrollable wild thoughts. Through Chan-Buddhist meditation, a practitioner seeks to attain the enlightened state of disclosing the internal spiritual power and wisdom.

2.2.3 Measures

Participants in both groups were requested to complete a Chinese version of the DASS (Depression Anxiety Stress Scales) questionnaire sheet (see Appendix C). The DASS (Lovibond and Lovibond 1995b) is a set of 42 items classified into three self-report scales capable of measuring the negative emotional states of depression, anxiety and stress/tension, respectively. The DASS evenly distributes 42 items for these three negative emotional states, that is, 14 items for evaluating each state. As the scales of DASS have been shown to have high internal consistency and to yield meaningful discrimination both in clinical and non-clinical samples (Lovibond and Lovibond 1995a; Brown *et al.* 1997; Antony *et al.* 1998; Clara *et al.* 2001; Crawford and Henry 2003), the scales should meet the needs of measuring current state of participants in three dimensions of depression, anxiety and stress/tension. However, it must be noted that the DASS Stress scale, originally labeled "tension/stress", measures the syndrome that is factorially (via confirmatory factor analysis) distinct from depression and anxiety characterized by nervous tension, difficulty in relaxing and irritability. It is narrower than the conventional conception of stress in terms of environmental events triggering a wide variety of emotional symptoms which probably incorporates all three DASS scales. Therefore, in most cases all three DASS scales are relevant to the assessment of stress in the broader sense.

Participants were asked to use 4-point scale (1: not at all, 2: some of the time, 3: a good part of time, and 4: most of the time) to rate the extent to which they had experienced the state described by each item over the past week. The recommended cutoffs for conventional severity labels (normal, mild, moderate, severe, and extremely severe) of each negative emotional state are provided in the DASS manual (Lovibond and Lovibond 1995b). It is helpful to characterize degree of severity relative to the reported statistics of general population.

On the questionnaire, experimental subjects were also requested to fill in (1) number of continuously practicing years after their 8-week Chan-meditation training, (2) averaging duration (in minutes) of each meditation practice during the past three months, and (3) averaging number of meditation practices per week during the past three months.

2.2.4 Procedure

The DASS questionnaires were administrated to the participants in the beginning of the semester (in March, 2005). Participants in the experimental group filled out the DASS questionnaires in their club congregation. Control group included the students attending the speech held by Chan club in the beginning of the semester, and the DASS questionnaires were administrated to them before the speech began. Figure 2-1 illustrates the flowchart of applying the DASS questionnaires.

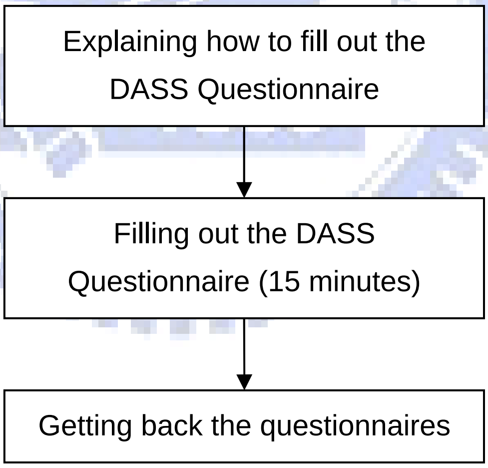


Figure 2-1. Flowchart of applying the DASS questionnaires.

2.3 Results

The percentage of participants with respect to different severity labels of three DASS scales, according to the DASS scale cutoffs (see Appendix C) provided in the DASS manual, are presented in Table 2-2 for respectively the experimental group and control group. Considering the Depression scale, 23% in the control group showed a depression level higher than “moderate”, which was only 2% in the experimental group. As regards the Anxiety scale, 38% of the control subjects had anxiety level higher than “moderate”, but only 19% of the meditation practitioners indicated their anxiety level higher than “moderate”. Finally, the Stress scale with level higher than “moderate” was declared by 17% of the control subjects and only 7% of the meditation practitioners. The results show that, in consideration of negative emotion, college students in Taiwan encounter the anxiety problem more than the depression and the stress. In addition, percentages of the students with all the three DASS scales at the level of “moderate” to “extremely severe” are all much lower in the experimental group than in the control group.

Table 2-2. Percentage of participants with respect to different severity labels of three DASS scales for the experimental group and control group

	Control Group (n=456)					Experimental Group (n=85)				
	Normal	Mild	Moderate	Severe	Extremely Severe	Normal	Mild	Moderate	Severe	Extremely Severe
Depression	55%	22%	17%	4%	2%	92%	6%	1%	1%	0%
Anxiety	52%	10%	26%	7%	5%	70%	11%	14%	4%	1%
Stress	50%	33%	12%	5%	0%	88%	5%	7%	0%	0%

Means and standard deviations of three DASS scales and their summation are presented in Table 2-3 for both groups. The summation of three DASS scales is labeled as “Total” which may present the stress level in the boarder sense. Student’s *t* test of the difference in means between two groups indicates that for all the three DASS scales and their summation, experimental-group means are significantly lower than those of the control group (Depression: t(194)=9.14, $p<0.001$; Anxiety: t(132)=5.39, $p<0.001$; Stress: t(539)=9.92, $p<0.001$; Total: t(138)=9.18, $p<0.001$). As a consequence, experimental group reveals significantly lower mean values on negative emotion than control group does.

Table 2-3. Means and standard deviations for DASS scales of experimental group and control group

	Control Group (n=456)		Experimental Group (n=85)		*p*-Value
	M	SD	M	SD	
Depression	9.26	6.75	4.45	3.88	0.000*
Anxiety	8.35	5.57	5.26	4.71	0.000*
Stress	14.28	6.06	7.25	5.65	0.000*
Total	31.88	16.47	16.95	13.19	0.000*

*Significantly different ($p<0.001$)

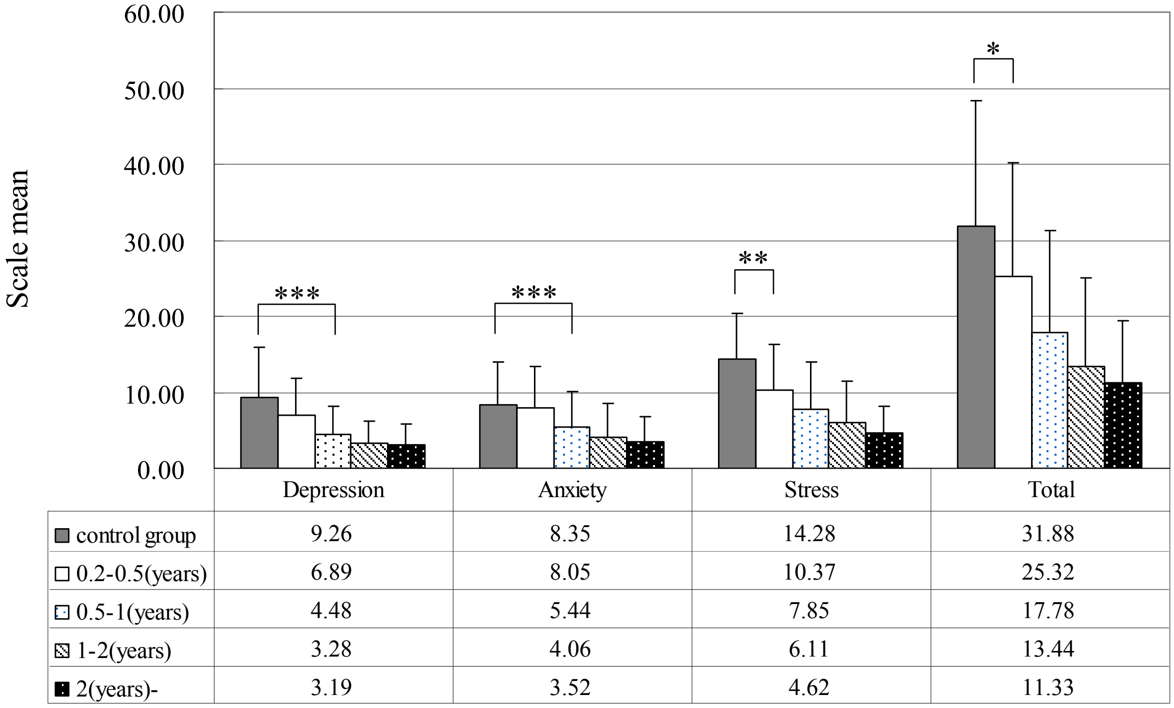
We further investigated the effect of three meditation factors (meditation experience, duration, and frequency) on the values of DASS scales. Table 2-4 lists the results of correlation coefficients between DASS scales and three meditation factors, respectively. Except for the Depression scale, all the DASS scales are significantly negatively related to meditation experience, meditation duration, and meditation frequency. Under (*p*-value) statistical significance, the Depression scale only negatively correlates with meditation experience. Generally, more meditation experience, longer meditation duration, and higher meditation frequency allow the negative emotional level perceived by subjects to drop further.

Table 2-4. Correlation coefficients between DASS scales and three meditation factors

	Meditation experience (years)	Meditation duration (minutes)	Meditation frequency (times/week)
Depression	-0.224*	-0.144	-0.193
Anxiety	-0.241*	-0.240*	-0.227*
Stress	-0.225*	-0.222*	-0.274*
Total	-0.248*	-0.223*	-0.255*

*Significantly related ($p<0.05$)

To further study the effect of meditation experience, the experimental subjects were divided into four groups of four ranges of practicing years, 0.2-0.5 years, 0.5-1 years, 1-2 years, and above 2 years. Figure 2-2 illustrates the mean values of DASS scales for each group. Practitioners with 0.2-0.5yr meditation experience have smaller mean values of DASS Stress scale than that of control subjects (Depression: t(473)=1.51, $p>0.05$; Anxiety: t(473)=0.23, $p>0.05$; Stress: t(473)=2.76, $p<0.005$; Total: t(473)=1.71, $p<0.05$). Accordingly, short-term meditation experience can be effective in reducing the level of stress/tension in college students. As regards the DASS Depression and Anxiety scales, mean values of the practitioners with 0.5-1yr meditation experience are significantly smaller than that of control subjects (Depression: t(37)=6.15, p<0.001; Anxiety: t(481)=2.66, p<0.001). This results show that long-term meditation experience is necessary for reducing depression and anxiety.



	Depression	Anxiety	Stress	Total
■ control group	9.26	8.35	14.28	31.88
□ 0.2-0.5(years)	6.89	8.05	10.37	25.32
⬚ 0.5-1(years)	4.48	5.44	7.85	17.78
▧ 1-2(years)	3.28	4.06	6.11	13.44
■ 2(years)-	3.19	3.52	4.62	11.33

Figure 2-2. Mean values of DASS scales with respect to different meditation experience (years) range of participants in experimental group. There are 19 participants for 0.2-0.5 years, 27 participants for 0.5-1 years, 18 participants for 1-2 years, and 21 participants for above 2 year. The Mean values of DASS scales of control group are also shown here. Significant difference are noted by * for p<0.05, ** for p<0.005, and *** for p<0.001.

Chapter 3 —
Heart Rate Variability in Chan Meditation

In regard to the significance of heart rate variability (HRV) in cardiovascular and autonomic functions, various interventions were studied to discover the way to regulate it. White (1999) studied the effects of relaxing music on HRV and found relaxing music could decrease the heart rate and increase the high-frequency HRV. Lehrer *et al.* (2000) developed a biofeedback system which could help practitioners to induce a resonant RSA (respiratory sinus arrhythmia) by slow breathing. Tiller *et al.* (1996) found that positive emotions could alter the HRV and lead to either the *entrainment* or *internal coherence* mode of heart function. Other mechanisms like yoga (Raghuraj *et al.* 1998), qigong (Lee *et al.* 2002) and meditation were also studied.

As introduced in Section 1.2, phenomenon of the HRV during various meditation techniques has been reported. However, most of these techniques emphasized the skill of slow breathing (<0.15Hz). This chapter reports our study on HRV during Chan-meditation which emphasizes inward attention. We analyzed the HRV both in time and frequency domains.

3.1 Introduction to ECG signal

Heart can beat by itself at a regular rhythm due to a specialized conducting system. The system comprises four parts, as shown in Fig. 3-1, SA node (sinoatrial node), AV node (atrioventricular node), Bundle of His, and Purkinje fibers. The SA node, locating in the right

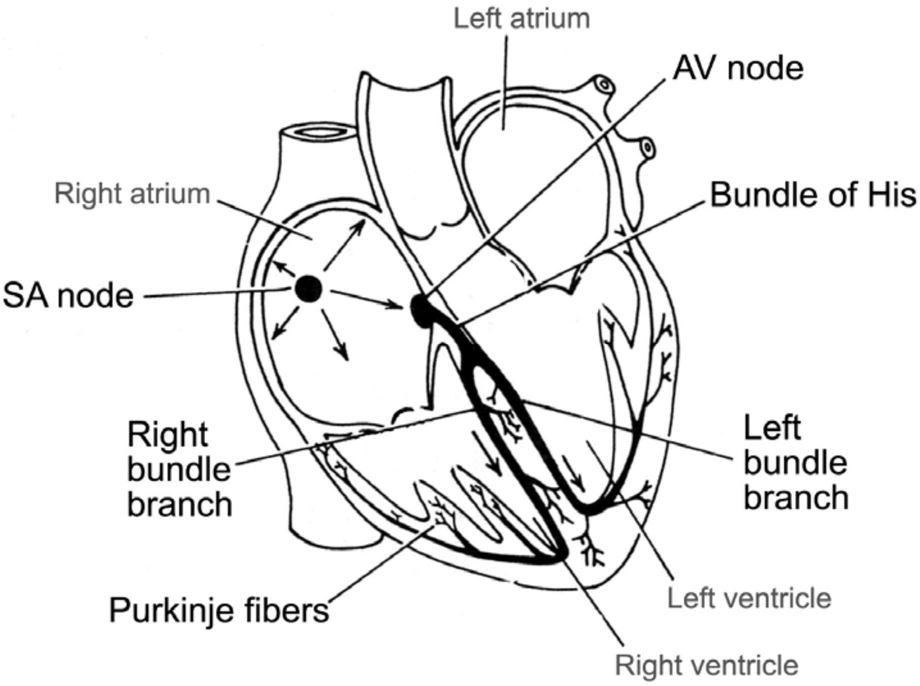


Figure 3-1. The conducting system of the human heart. (Modified from Shepherd 1988).

atrium of the heart, is the pacemaker that controls the heart rate. Depolarization waves are generated by SA node and propagate to atria, AV node, and ventricles. When depolarization waves propagate to atria, they make the atria contract. These waves afterwards spread to AV node that connects with Bundle of His. Purkinje fibers are the extended parts of Bundle of His. The networking of Purkinje fibers appears to be a threadlike net on subendocardial surface. Therefore, through Bundle of His, depolarization waves spread to entire ventricles and make two ventricles contract at the same time. In sum, the pathway of cardiac electrical conduction is: SA node → atria → AV node → Bundle of His → Bundle branches of His → Purkinje fibers → ventricles (Shepherd 1988).

The depolarization waves not only spread throughout the whole heart, but also induce the electrical current change that can be non-invasively recorded on the body surface as the electrocardiogram (ECG) signal. Without stimulation, the heart cells are in the quiescent state (approximate -80 mV) with negative potential (so-called polarization). Once being stimulated, they bear positive potential and the systole reaction is induced. Hence, ECG reflects the potential variation of cardiac cycle of the heart. The typical wave complex of ECG is shown in Fig. 3-2. Each ECG complex correlates to the particular task of the cardiac cycle as described below:

1. P wave: The wave is due to the depolarization of atria. Atria contract at this time.
2. Q wave: The wave is caused by the depolarization of ventricles, and the R wave follows. Atria relax at this time.
3. R wave: The period of the depolarization of ventricles. Atria relax gradually, and ventricles start to contract at this moment.
4. S wave: The period of the depolarization of ventricles. Atria completely expand, and ventricles completely contract.
5. T wave: This wave is due to the repolarization of ventricles. Ventricles expand gradually.

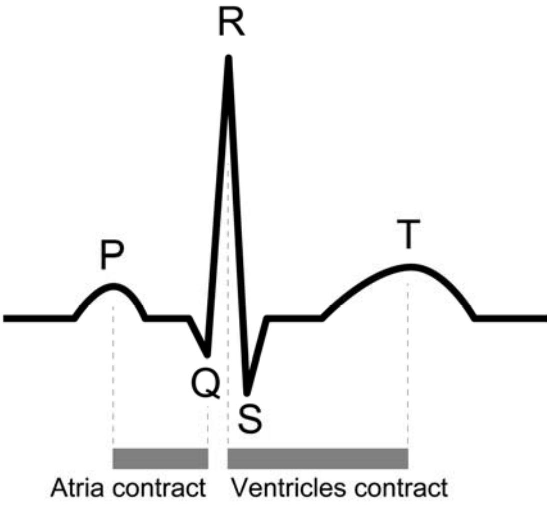


Figure 3-2. The typical wave complex of ECG.

3.2 Introduction to heart rate variability

3.2.1 Autonomic nervous system and heart rate variability

The autonomic nervous system (ANS) is a control system responsible for maintaining the homeostasis in the body. Autonomic nervous system involves the sympathetic nervous system and parasympathetic nervous system. They are distributed to smooth muscles, cardiac muscles, and glands (see Fig. 3-3). The ANS affects bodily involuntary functions such as heart rate, blood pressure, respiratory rate, and digestion, etc. Most autonomic functions are controlled through the interaction between sympathetic and parasympathetic nerves in a counterbalance way, few (e.g., adrenal medulla) are controlled by only one of these two branches of ANS. In general, the sympathetic nervous system is responsible for the stress response when you encounter a stressor, and the parasympathetic nervous system is responsible for the relaxation response when the stressor has disappeared.

As mentioned in Section 3.1, the heart rate is controlled by the SA node. The SA node has an inherent constant firing rate of about 100 times per minute (Vander *et al.* 1994). This firing rate is modulated by the ANS that is mediated by the sympathetic and parasympathetic nerves innervated onto the SA node (see Fig. 3-4). The autonomic control over SA node may increase (via the sympathetic nerves) or decrease (via the parasympathetic nerves) the heart rate, according, causing fluctuations in heart rate. This fluctuation (change of beat-to-beat intervals) in heart rate is named as HRV. It reflects the modulation of ANS on heart rate. Clinical application of HRV was first reported in 1965 by Hon and Lee. The reduction in HRV has been found to be correlated with several diseases (Hon and Lee 1965; Ewing *et al.* 1985; Kleiger *et al.* 1987; Singh *et al.* 1998; Bilchick *et al.* 2002).

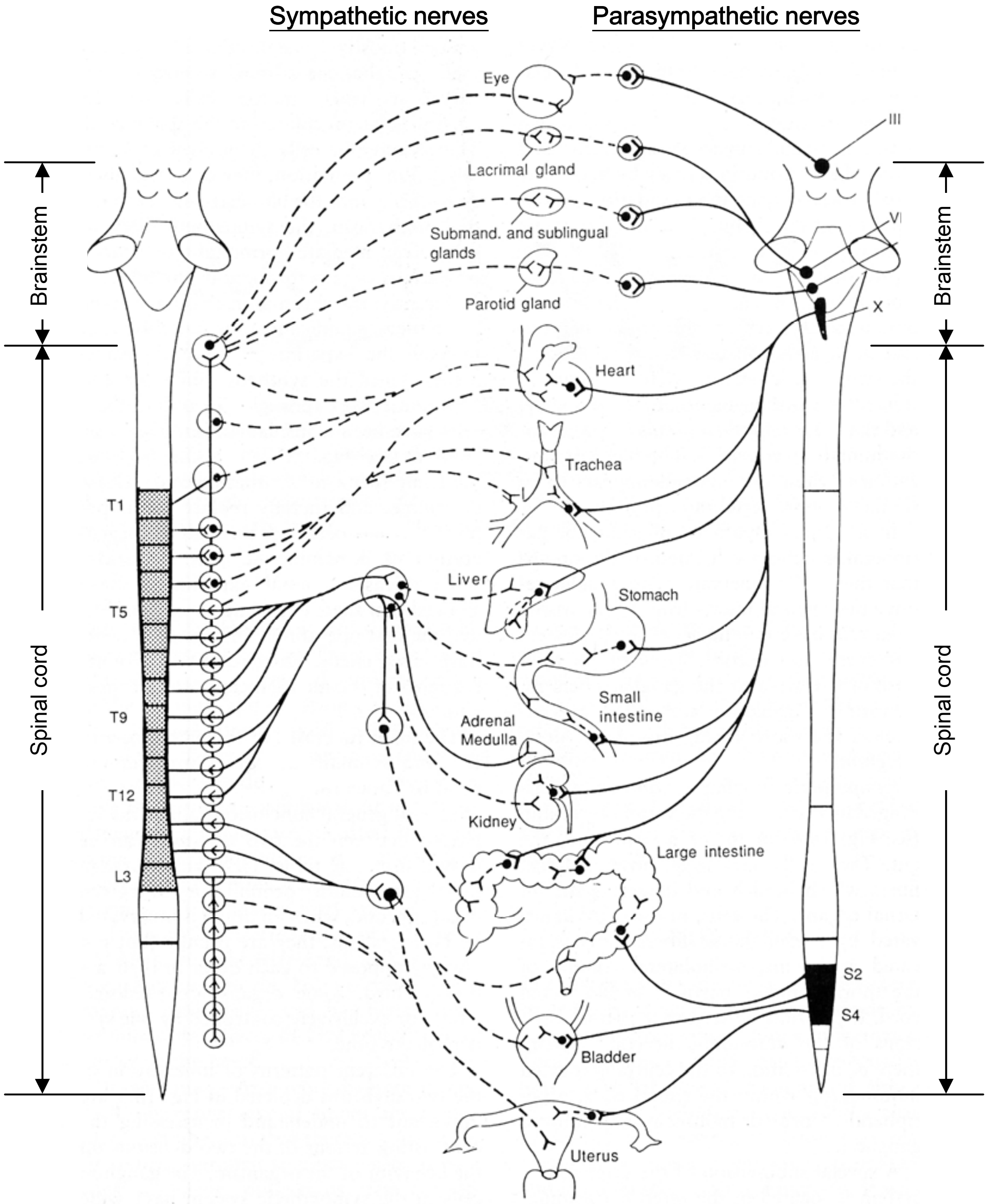


Figure 3-3. Organization of the autonomic nervous system: the sympathetic (left) and parasympathetic (right) branches. (Modified from Shepherd 1988).

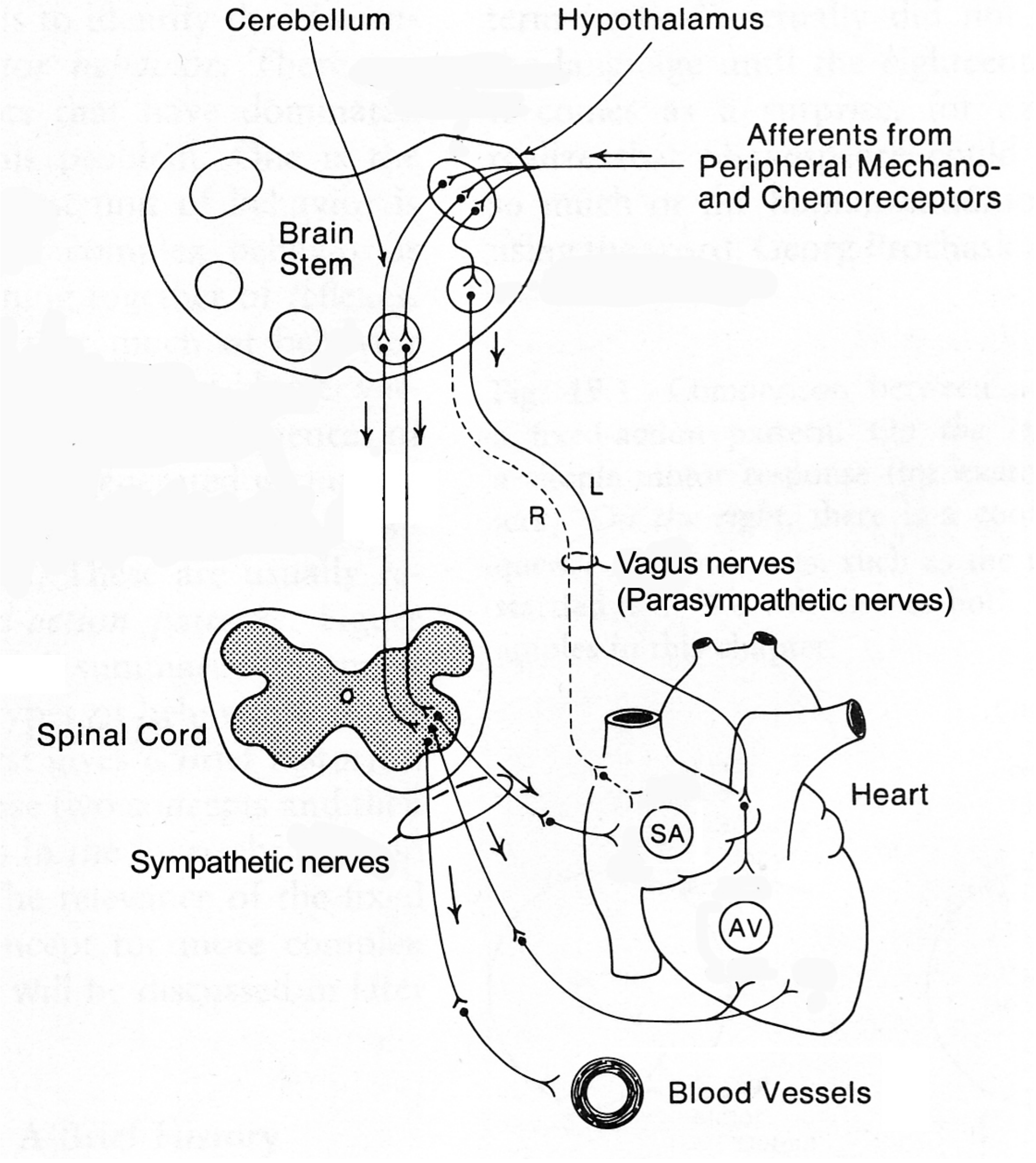
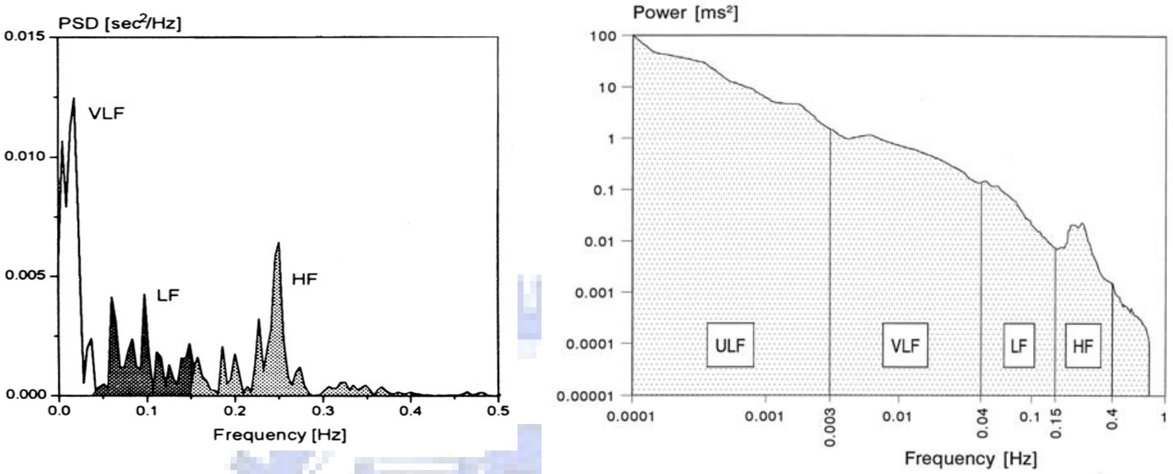


Figure 3-4. The autonomic innervations of the heart. (Modified from Shepherd 1988).

3.2.2 Methods for analyzing heart rate variability

A number of methods have been developed for analyzing the HRV. These methods can be grouped into two categories: linear and nonlinear. Linear methods involve time domain analysis and frequency domain analysis. In the time domain analysis, the intervals between successive normal heartbeats should be determined. In the ECG signal, each R peaks is detected, and the so-called normal-to-normal (NN) intervals (that is all intervals between adjacent R peaks of heartbeats resulted from sinus node depolarization) are determined. Then the time domain parameters such as the mean of NN intervals, the standard deviation of NN intervals (SDNN), the root-mean-square of differences between adjacent NN intervals (RMSSD), etc (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996) can be calculated. These parameters are generally derived over 24-hour long-term recordings, or over short-term recordings using a 5-minute window. In the frequency domain analysis, constructed sequences of the NN intervals can be analyzed by Fast Fourier Transform (FFT) or autoregressive model. Similar to the time domain analysis, frequency domain analysis can be applied to either 24-hour long-term recordings or 5-minute short-term epochs extracted from the entire recordings. In the short-term analysis, three main spectral components have been found to reveal physiological correlation: very low frequency (VLF, 0.003-0.04 Hz), low frequency (LF, 0.04-0.15 Hz), and high frequency (HF, 0.15-0.4 Hz), as shown in Fig. 3-5(a). In the long-term analysis, researchers have been also interested in an ultra-low-frequency (ULF) component slower than 0.003 Hz (Fig. 3-5(b)), in addition to VLF, LF, and HF components.

Methods based on the nonlinear model or hypothesis include Poincaré plot (Brennan *et al.* 1998; D'Addio *et al.* 1999), Lyapounov exponents measurement (Pierro *et al.* 1998), 1/f behavior (Lessard *et al.* 1999), approximate entropy measurement (Gu *et al.* 2000), and Geometrical methods (Woo *et al.* 1992), etc. Nonlinear methods provide a feasible tool to explore the nonlinear mechanisms underlying the HRV. However, nonlinear methods for HRV analysis still require further studies to obtain meaningful interpretation and reliable application in medicine.



(a) (b)

Figure 3-5. Power spectral examples of NN-interval sequences derived from (a) a 5-minute ECG and (b) a 24-hour ECG (The Y axis is power in log). (Modified from Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996).

3.2.3 Physiological correlates of HRV spectral components

With power spectrum analysis, the fluctuations of heart rate are divided into four frequency bands (ULF, VLF, LF, and HF) which correspond to different physiological phenomena (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996). The high-frequency (HF, 0.15-0.4 Hz) and low-frequency (LF, 0.04-0.15 Hz) components are the two that are better understood and mostly used. The HF component is mainly contributed by parasympathetic modulation. The LF component corresponds to mixed sympathetic and parasympathetic modulation. And the LF/HF ratio is considered as an indicator of sympathovagal balance (Eckberg 1997). The LF and HF components may be measured with normalized unit (LF norm and HF norm) which represents the relative value of each power component in proportion to the total power of LF and HF component, respectively. Similar to LF/HF ratio, LF norm and HF norm can also reflect the balance between sympathetic and parasympathetic activities.

3.3 Experimental setup

3.3.1 Subjects

Two groups of subjects were studied in this work. The experimental group included 10 experienced Chan-meditation practitioners (3 female and 7 males, mean age 27.0±2.4 years; mean meditation experience 6.0±3.2 years); the control group included 10 non-meditators (1 female and 9 males, mean age 26.2±3.6 years). All subjects had no cardiac, pulmonary, and other chronic diseases according to their medical records. Also, all subjects were non-smokers, neither caffeine addicts nor alcohol addicts. Each subject provided written informed consent (in accordance with the Helsinki Declaration) to the study.

3.3.2 Procedure

Because the human cardiac function is regulated differently by ANS in a day (Nakagawa *et al.* 1998), the experiments were conducted during the same period (3:30pm to 5:00pm) to ensure similar states of ANS for all subjects. The experiments comprised two sessions (Fig. 3-6). During Session 1 (baseline phase), subjects of both groups rested, in a ~70° head-up back-tilt position with eyes closed, for 10 min. During Session 2, subjects of control group continued resting for 20 min; while experimental subjects began meditating for 20 min. Experimental subjects, following their routine meditation convention, meditated at full- or half-lotus posture, with eyes closed. During meditation, practitioners concentrated their mind on “Chan Chakra” locating inside the third ventricle of human brain. All subjects breathed spontaneously in both sessions.

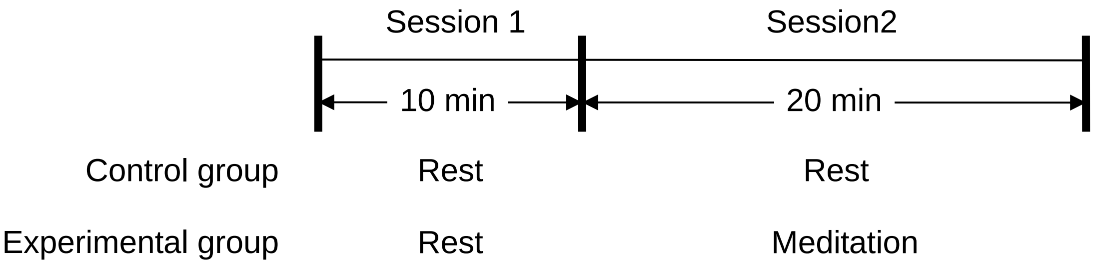
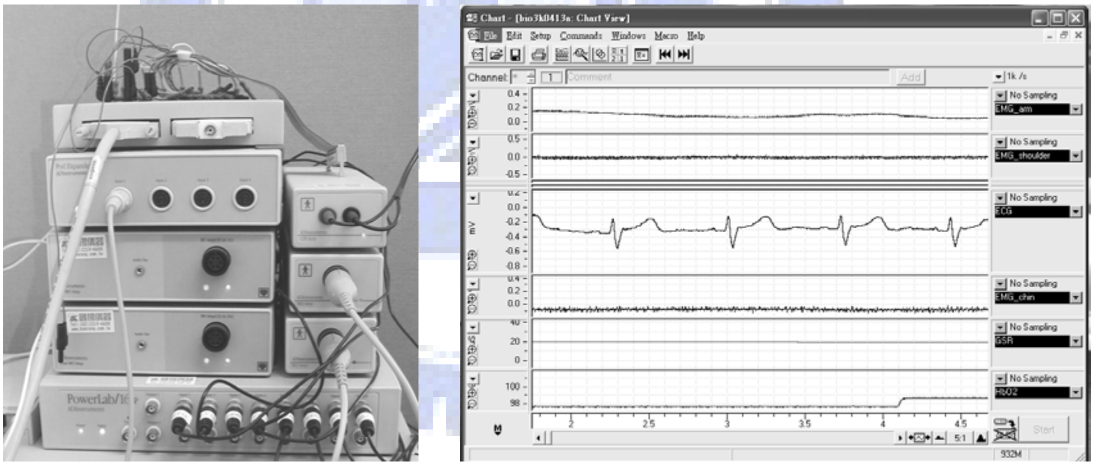


Figure 3-6. Experimental procedure.

3.3.3 Signal acquisition



(a) (b)

Figure 3-7. Physiological signal recording system: (a) Bio-amplifiers, and (b) digitization and on-line monitoring system.

The ECG and respiration signals were recorded simultaneously at 1000 Hz sampling rate using PowerLab/16SP recording system (ADInstruments, Sydney, Australia; see Fig. 3-7). Furthermore, the ECG signal was pre-filtered by a 0.3-200 Hz bandpass filter, and the respiratory signal was pre-filtered by a lowpass filter with cutoff frequency of 5 Hz. A 60-Hz notch filter was applied to remove artifacts from power line or the surroundings.

The ECG signal was recorded using Lead Ⅰ of standard bipolar limb leads (Carr and Brown 2000), as shown in Fig. 3-8. Recording site on the left (right) arm was connected to the amplifier’s positive (negative) input; while the ground was placed on the inside of left ankle. The disposable ECG electrode (Medi-Trace 200 Foam Electrodes, Kendall, Chicopee, MA, USA) shown in Fig. 3-9(a) was applied in this experiment. The respiratory signal was recorded using a piezo-electric transducer (Model 1132 Pneumotrace II (R), UFI, Morro Bay, CA, USA), as shown in Fig. 3-9(b), wrapped around the belly covering the navel.

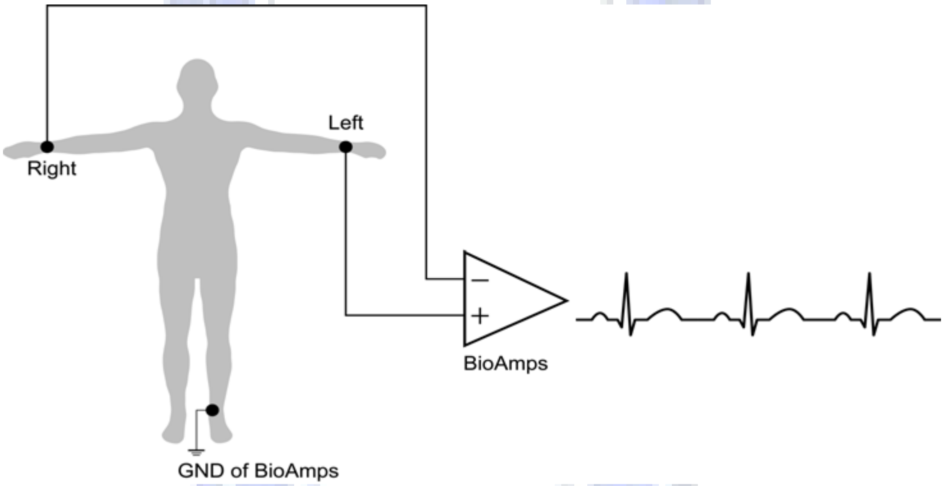
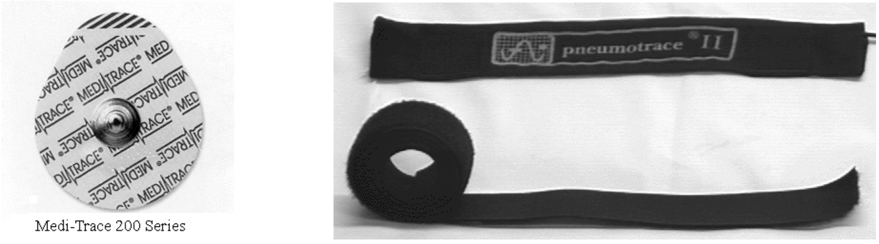


Figure 3-8. Lead Ⅰ configuration of standard bipolar limb leads.



(a) (b)

Figure 3-9. (a) Disposable ECG electrode, and (b) Piezo-electric respiratory transducer.

3.4 Signal analysis

3.4.1 Heart rate variability

In this study, we analyzed HRV in time domain and frequency domain. Figure 3-10 illustrates the flowchart of HRV analysis.

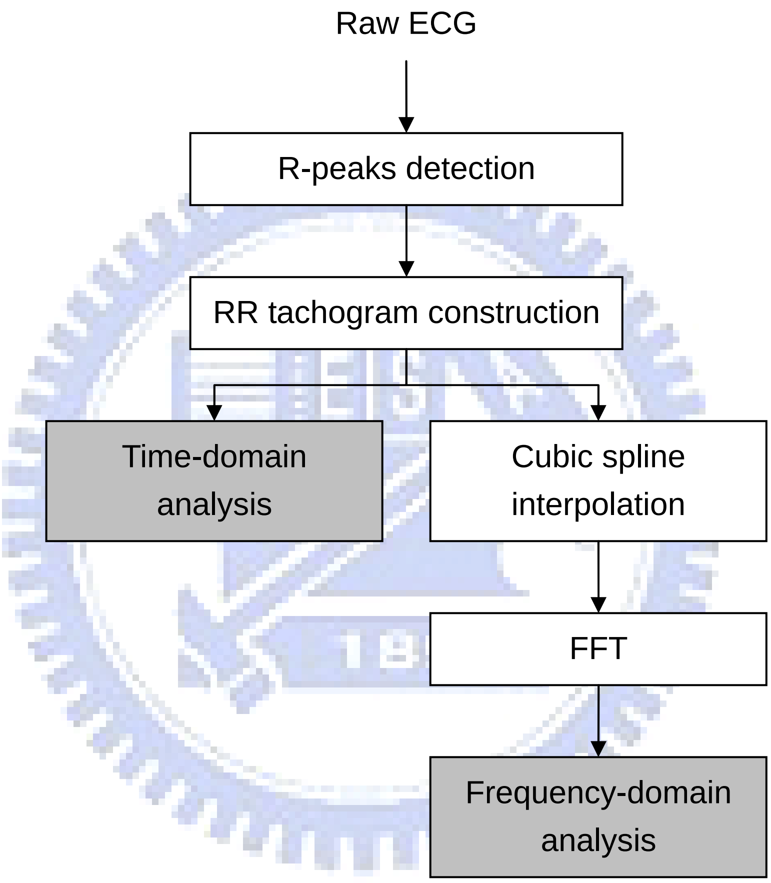


Figure 3-10. Flowchart of HRV analysis.

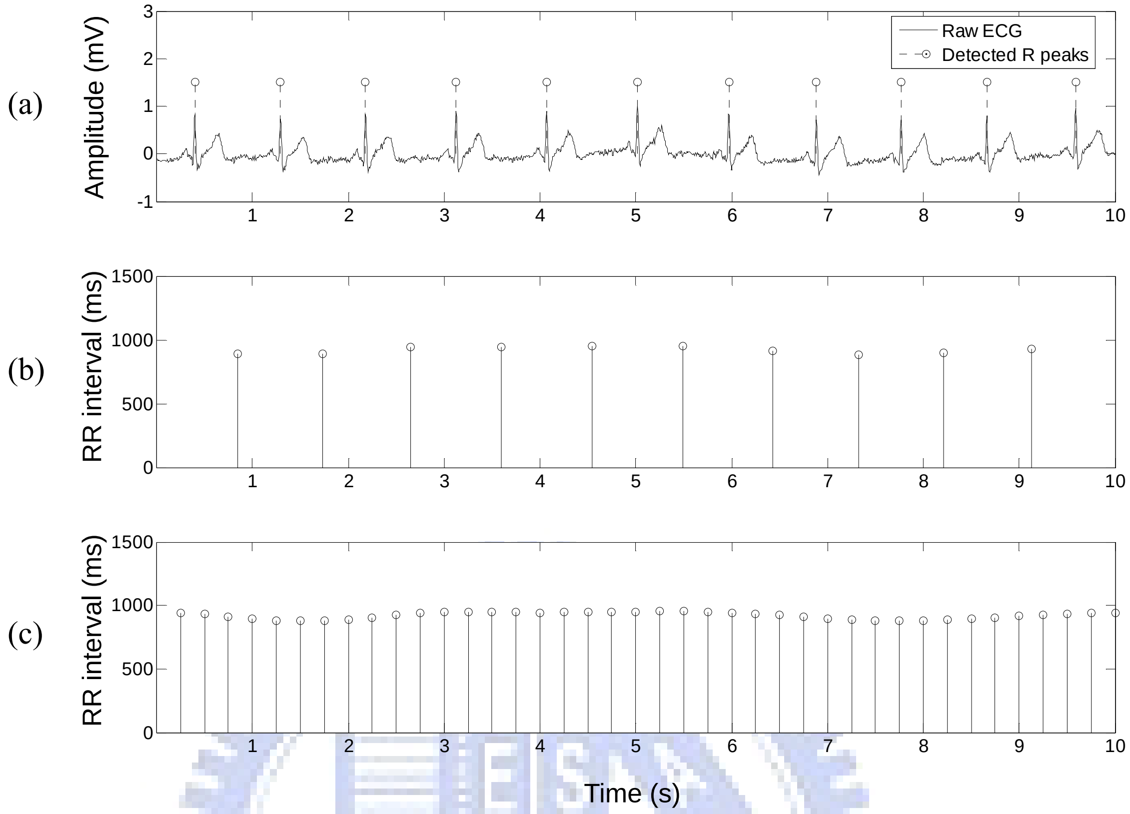


Figure 3-11. (a) Raw ECG and the R peaks detected, (b) RR tachogram, and (c) uniform-sampling RR-interval sequence.

Step 1. R-peaks detection

As shown in Fig. 3-11(a), R peaks of the ECG signal were detected automatically by the algorithm described in Appendix D and reviewed manually.

Step 2. RR tachogram construction

The R-R intervals (in ms) were then calculated to construct the RR tachogram (R-R interval series), as shown in Fig. 3-11(b). In time-domain analysis, the R-R interval series were used.

Step 3. Cubic spline interpolation

Frequency-domain analysis based on Fourier transform assumes equal sampling period of the series (that is, uniform sampling process). However, RR tachogram constructed from R-R intervals explicitly is a non-uniform sampled sequence. Therefore, before frequency-domain analysis, we resampled the RR tachogram using cubic spline interpolation at 4 Hz to re-construct a uniform-sampled RR-interval sequence (see Fig. 3-11(c)). Figure 3-12 shows the power spectrum of an RR-interval sequence constructed from a 5-minute ECG.

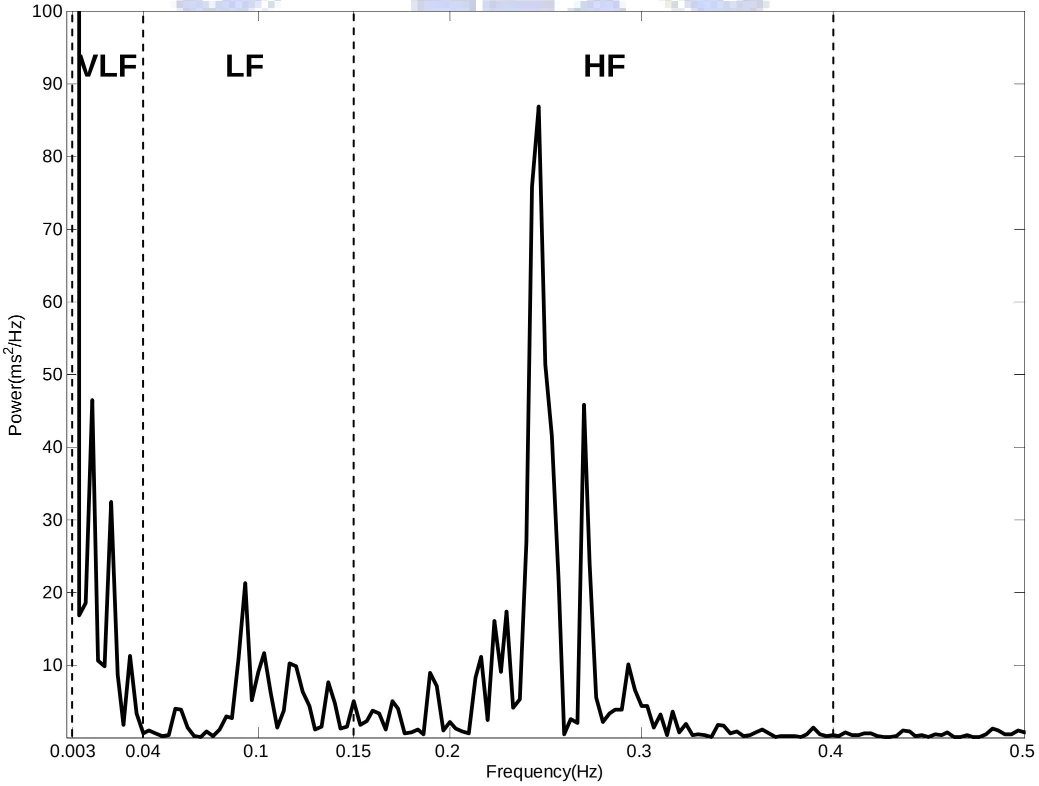


Figure 3-12. Power spectrum of an RR-interval sequence constructed from a 5-minute ECG using FFT. The regions of VLF, LF, and HF components are marked.

Table 3-1 lists the HRV parameters to be analyzed with their abbreviations. All the parameters were calculated using 5-minute window without overlap throughout the recordings.

Table 3-1. Parameters of HRV analysis applied in this study

Parameter	Units	Description
Time domain		
Mean HR	beats/min	Mean heart rate
SDNN	ms	Standard deviation of NN intervals
RMSSD	ms	Root-Mean-Square of the differences between adjacent NN intervals
Frequency domain		
LF	ms^2	Power in low frequency band (0.04-0.15 Hz)
HF	ms^2	Power in high frequency band (0.15-0.4 Hz)
LF norm	%	LF/(LF+HF)×100
HF norm	%	HF/(LF+HF)×100
LF/HF		LF/HF

3.4.2 Respiration rate

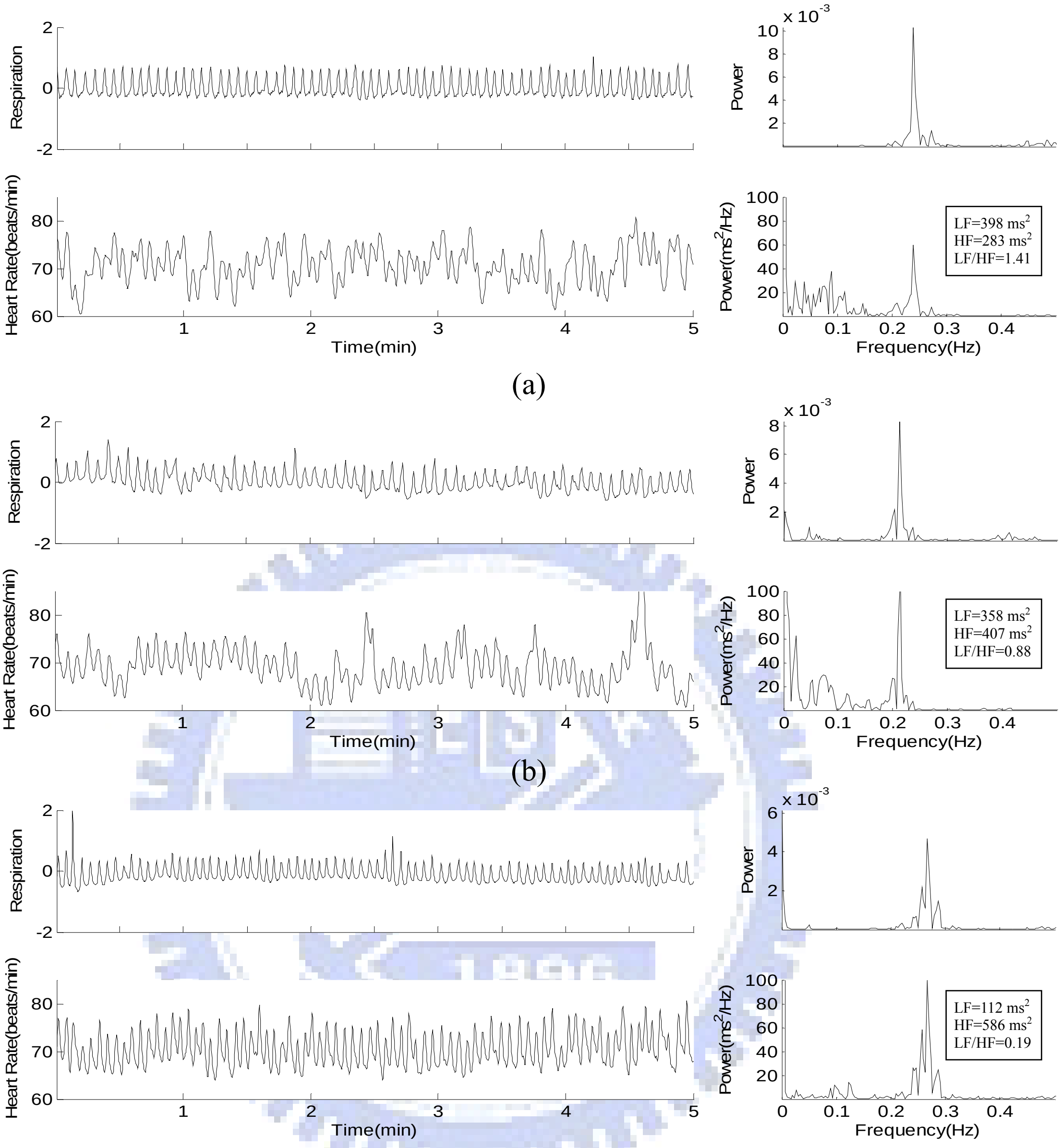
Since the respiration rate significantly affects HRV (Song and Lehrer 2003), we considered it as an important reference in HRV research. To determine the respiration rate, respiration signal was first filtered by a 0.04-0.4 Hz bandpass filter to reduce the baseline drift and high-frequency noise. Then the inspiration-phase peaks of filtered respiratory signal were detected. For each 5-minute segment, the mean respiration rate (breaths/min) was calculated by counting the numbers of inspiration-phase peaks and dividing by 5.

3.5 Statistical analysis

Before statistic analysis, the mean values of parameters were calculated for each subject in each session by averaging results derived from 5-minute segments. We used SPSS (version 12.0 for Windows) for statistical analysis. Two-way ANOVA (2 groups × 2 sessions) with repeated measures was used to evaluate the statistical differences between groups (inter-group) and between sessions (inter-session) for each parameter. Two main effects (group and session) and the interaction effect (group × session) were verified. When two-way ANOVA revealed significant interaction, we performed simple effects analysis for each group and also for each session. The statistically significant level was set at 0.05, and comparisons were two tailed.

3.6 Results

Figure 3-13 displays three typical heart rate signals during experiments, together with the respiration signals and their power spectra. Figure 3-13(a) presents the results of a control subject at rest; while Figs. 3-13 (b) and 3-13(c) plot the results of two experimental subjects during meditation. For the control subjects at rest, the mean value of LF/HF ratio was about 1.5 and the oscillations of their heart rate signals were much irregular (Fig. 3-13(a)). For the experimental subjects during meditation, most of them exhibited lower level of LF/HF ratio (< 1), compared to the control subjects during rest. In this state, the heart rate signals revealed segments of regular oscillations (Fig. 3-13(b)). A couple of experimental subjects presented a very low level of LF/HF ratio (<0.3) and the oscillations of their heart rate signals were much regular as shown in Fig. 3-13(c).



(a)

(b)

(c)

Figure 3-13. Three typical heart rate and simultaneous respiratory signals during rest and meditation; on the right are their power spectra: (a) a control subject during rest in which presented normal LF/HF level, (b) an experiment subject during meditation in which presented low LF/HF level, and (c) another experimental subject during meditation in which presented very low LF/HF level.

The results of respiration rate are summarized in Table 3-2. The mean values of respiration rates do not show significant difference between groups and between sessions by two-way ANOVA analysis. Hence in this study, we can exclude the effect of respiration rate on HRV. We further compared the HRV results in the following sub-sections.

Table 3-2. Mean values and standard deviations of respiration rate during two experimental sessions for control and experimental groups

	Control Group (n=10)		Experimental Group (n=10)		*p*-Value		
	Session 1 (Baseline)	Session 2 (Rest)	Session 1 (Baseline)	Session 2 (Meditation)	Group effect	Session effect	Interaction effect
Respiration rate (breaths/min)	16.1±3.0	16.1±2.9	15.0±2.0	15.1±2.4	NS	NS	NS

NS = not significant; *Significant difference ($p<0.05$).

3.6.1 Time-domain HRV parameters

As shown in Table 3-3, we observed significant interaction (group × session) effects for Mean HR [$F(1,18)=7.39$, $p=0.014$] and SDNN [$F(1,18)=4.71$, $p=0.044$], which suggested a significant difference between groups in session effects. Further tests of simple effects revealed that there was a significant increase of mean heart rate for experimental subjects from Session 1 to Session 2 [$F(1,18)=6.51$, $p=0.02$], but no significant difference for the control subjects. And experimental subjects had a significantly higher mean heart rate than control subjects during Session 2 [$F(1,36)=7.73$, $p=0.009$]. There appeared a significant increase of SDNN only for control subjects from Session 1 to Session 2 [$F(1,18)=6.64$, $p=0.019$]. And control subjects had a significantly higher SDNN than experimental subjects during Session 2 [*F*(1,36)=5.15, *p*=0.029]. There existed neither significant main effect nor interaction effect for parameter RMSSD.

Table 3-3. Mean values and standard deviations of time-domain HRV parameters during two experimental sessions for control and experimental groups

	Control Group (n=10)		Experimental Group (n=10)		*p*-Value		
	Session 1 (Baseline)	Session 2 (Rest)	Session 1 (Baseline)	Session 2 (Meditation)	Group effect	Session effect	Interaction effect
Mean HR (beats/min)	67.4±6.7	65.6±5.7	70.7±8.2	74.3±7.2	NS	NS	0.014*
SDNN (ms)	53.3±13.0	60.8±16.7	48.3±10.7	46.9±13.5	NS	NS	0.044*
RMSSD (ms)	43.0±17.8	47.7±16.7	36.4±11.8	38.1±14.2	NS	NS	NS

NS = not significant; *Significant difference (p<0.05).

3.6.2 Frequency-domain HRV parameters

As shown in Table 3-4, there were significant session effects for LF power [*F*(1,18)=8.01, *p*=0.011] and HF power [*F*(1,18)=10.09, *p*=0.005]. For both groups, the LF power and HF power both significantly increased from Session1 to Session 2. There were significant interaction (group × session) effects for LF norm [*F*(1,18)=6.39, *p*=0.021], HF norm [*F*(1,18)=6.39, *p*=0.021] and LF/HF [*F*(1,18)=5.33, *p*=0.033]. Further tests of simple effects revealed that there were significant decreases of LF norm [*F*(1,18)=9.62, *p*=0.006] and LF/HF [*F*(1,18)=5.94, *p*=0.025], and a significant increase of HF norm [*F*(1,18)=9.62, *p*=0.006] for experimental subjects from Session 1 to Session 2. During Session 2, experimental subjects had significantly lower LF norm [*F*(1,36)=5.94, *p*=0.02] and LF/HF [*F*(1,36)=5.19, *p*=0.029], and significantly higher HF norm [*F*(1,36)=5.94, *p*=0.02] than control subjects.

Table 3-4. Mean values and standard deviations of frequency-domain HRV parameters during two experimental sessions for control and experimental groups

	Control Group (n=10)		Experimental Group (n=10)		*p*-Value		
	Session 1 (Baseline)	Session 2 (Rest)	Session 1 (Baseline)	Session 2 (Meditation)	Group effect	Session effect	Interaction effect
LF (ms^2)	451±264	690±463	286±219	322±342	NS	0.011*	NS
HF (ms^2)	380±254	469±299	297±165	401±241	NS	0.005*	NS
LF norm (%)	54.0±12.2	55.2±11.2	48.4±16.2	40.6±13.6	NS	NS	0.021*
HF norm (%)	46.0±12.2	44.8±11.2	51.6±16.2	59.4±13.6	NS	NS	0.021*
LF/HF	1.37±0.58	1.48±0.61	1.16±0.78	0.83±0.53	NS	NS	0.033*

NS = not significant; *Significant difference ($p<0.05$).

Chapter 4 — Cardiorespiratory Phase Synchronization of Chan-Meditation Practitioners

The cardiac and respiratory systems can be viewed as two self-sustained oscillators with various interactions between them. In this chapter, the cardiorespiratory phase synchronization (CRPS) quantified by synchrogram was investigated to explore the phase synchronization between these two systems. The synchrogram scheme was applied to electrocardiogram (ECG) and respiration signals. Particular focus was the distinct cardiac-respiratory regulation phenomena intervened by inward-attention meditation and normal relaxation.

4.1 Introduction to cardiorespiratory interaction

The interaction between human cardiac and respiratory systems has been widely studied for many decades. The action of these two systems has been found to not be independent, with the two systems instead being coupled by various mechanisms. One well-known phenomenon of cardiorespiratory interaction is the respiratory modulation of heart rate, which is known as respiratory sinus arrhythmia (RSA) (Berntson *et al.* 1993). RSA portrays heart rate variability in synchrony with respiration; that is, heart rate increases during inspiration and decreases during expiration. RSA can increase the efficiency of human pulmonary air exchange (Giardino *et al.* 2003). Besides modulation, another cardiorespiratory interaction, phase synchronization, has recently been studied.

In 1998, Schäfer *et al.* applied the concept of phase synchronization of chaotic oscillators (Rosenblum *et al.* 1996) to the development of a technique called *synchrogram* to analyze irregular, non-stationary bivariate data. Using this method, they found CRPS of several locking ratios (ratios of heartbeat frequencies to respiratory frequencies) occurring in healthy young athletes at rest. This overthrew the widely accepted knowledge that cardiac and respiratory rhythms in humans were unsynchronized. Several subsequent studies followed the synchrogram method and presented the phenomenon of CRPS in different subjects (Schäfer *et al.* 1999; Lotrič and Stefanovska 2000; Mrowka *et al.* 2000; Stefanovska *et al.* 2000; Stefanovska *et al.* 2001; Toledo *et al.* 2002; Bartsch *et al.* 2007).

According to previous studies (Raschke 1991; Toledo *et al.* 2002), CRPS may establish an effectual co-action between cardiac and respiratory systems which can preserve the body energy. Compared with RSA being stable even under cognitive arousal, CRPS was most visible under conditions of low cognitive activity, such as during sleep (Bartsch *et al.* 2007; Raschke 1991) and anesthesia (Galletly and Larsen 1997; Stefanovska *et al.* 2000), and was almost lost during physical strain (Raschke 1991). It is because that under low cognition, brain activity may interfere less with the coordination between the cardiac and respiratory systems and facilitate the emergence of CRPS (Bartsch *et al.* 2007). Additionally, the mechanism of CRPS is different from that of RSA. The coupling direction of RSA is mainly from respiration to heartbeat, whereas CRPS is more likely to be achieved by adjusting respiration to heart beat (Toledo *et al.* 2002; Galletly and Larsen 1997). Mrowka *et al.* (2000) suggested that the nerves coming from the arterial baroreceptor provide the respiratory center (in brain stem) with information regarding blood pressure for adjusting respiration rhythm.

4.2 The synchrogram method

4.2.1 Definition of phase synchronization

By definition, synchronization is a particular phenomenon that occurs due to interaction between two or more self-sustained oscillators (Pikovsky *et al.* 2003). Among various types of synchronization, *phase synchronization* is characterized by the locking of phases of self-sustained oscillators despite their amplitudes possibly remaining uncorrelated. Consider the special case of periodic self-sustained oscillators. The phase locking mechanism is described by the phase relationship below:

$$\varphi_{n,m} = n\phi_1 - m\phi_2 = \text{const}\,, \tag{4-1}$$

where n and m are integers, ϕ_1 is the phase of slow oscillator and ϕ_2 is the phase of fast oscillator, and $\varphi_{n,m}$ is the *generalized phase difference*. Note that the values of ϕ_1 and ϕ_2 are not bounded in the range $[0,\ 2\pi]$. According to eq. (4-1), oscillator 1 completes m cycles while oscillator 2 completes n cycles. It is called $n:m$ *phase synchronization*.

Consider the case of nonlinear oscillators that are most likely occurred in physical systems. A more general form of eq. (4-1) is required to cope with the subtle drift of periods. We then propose a weaker condition for phase locking below:

$$\left|\varphi_{n,m} - \text{const}\right| < \delta\,. \tag{4-2}$$

In such cases, the $n:m$ phase locking is manifested by the tolerance variation δ of $\varphi_{n,m}$ around a horizontal plateau.

In practical applications, noise interference is inevitable. We thus need to modify eq. (4-2) for the possible condition of accumulation of multiple noise components originated from the oscillator itself, measurement, or algorithm. Weak noise may cause $\varphi_{n,m}$ to simply fluctuate around a constant value. On the other hand, strong noise can cause a phase slip of

2π. As a consequence, the *cyclic relative phase* $\Psi_{n,m}$ is used instead of $\varphi_{n,m}$ to avoid the influence of phase slips due to noise. By modulo operation, $\Psi_{n,m}$ can be obtained below:

$$\Psi_{n,m} = \varphi_{n,m} \bmod 2\pi, \tag{4-3}$$

where 'mod' performs the modulo operator on $\varphi_{n,m}$ so that the result $\Psi_{n,m}$ is within the range $[0, 2\pi)$. Then the phase synchronization can be understood as the appearance of a peak in the distribution of the cyclic relative phase $\Psi_{n,m}$.

4.2.2 Synchrogram method

According to eq. (4-3), the plot of $\Psi_{n,m}$ versus time is the straightforward approach to analyze the phase synchronization. However, a disadvantage of this method is that only one specific $n:m$ phase synchronization can be observed in one plot, without the information of transitions between different $n:m$ phase synchronizations. To resolve this problem, the synchrogram method was introduced (Schäfer *et al.* 1999). To construct the synchrogram, we need to determine the *normalized relative phase* $\psi_m(t_k)$ of oscillator 2 within m cycles of oscillator 1:

$$\psi_m(t_k) = \frac{1}{2\pi}\left[\phi_1(t_k) \bmod 2\pi m\right], \tag{4-4}$$

where $\phi_1(\cdot)$ is the instantaneous phase of oscillator 1, and t_k is the time of the *k*th marker events of oscillator 2. The modulo operation '$\bmod (2\pi m)$' denotes wrapping the phase values into the interval $[0, 2\pi m)$, that is, m consecutive cycles of oscillator 1 are integrated into one longer cycle). Finally, the plot of $\psi_m(t_k)$ against t_k forms the synchrogram.

As an illustration, the synchrogram with $m = 2$ is shown in Fig. 4-1. It presents n dots within m consecutive cycles of oscillator 1. In the ideal case of $n : m$ synchronization, phase ϕ_1 within m cycles of oscillator 1 (or, ϕ_1 grows from 0 to $2\pi m$) presents the same value of normalized relative phase at time t_k and t_{k+n}, that is, $\psi_m(t_k)=\psi_m(t_{k+n})$. For example, $\psi_m(t_k)=\psi_m(t_{k+3})$ for the case of good synchronization illustrated in Fig. 4-2. In consequence, the synchrogram will exhibit n horizontal lines. One advantage of this display tool is that only one integer of parameter m needs to be determined. Then, several synchronous events with different integers of parameter n can be derived within one plot. As a consequence, various $n:m$ synchronization states can be scrutinized based on a fixed value of m so that the transitions between them can be traced.

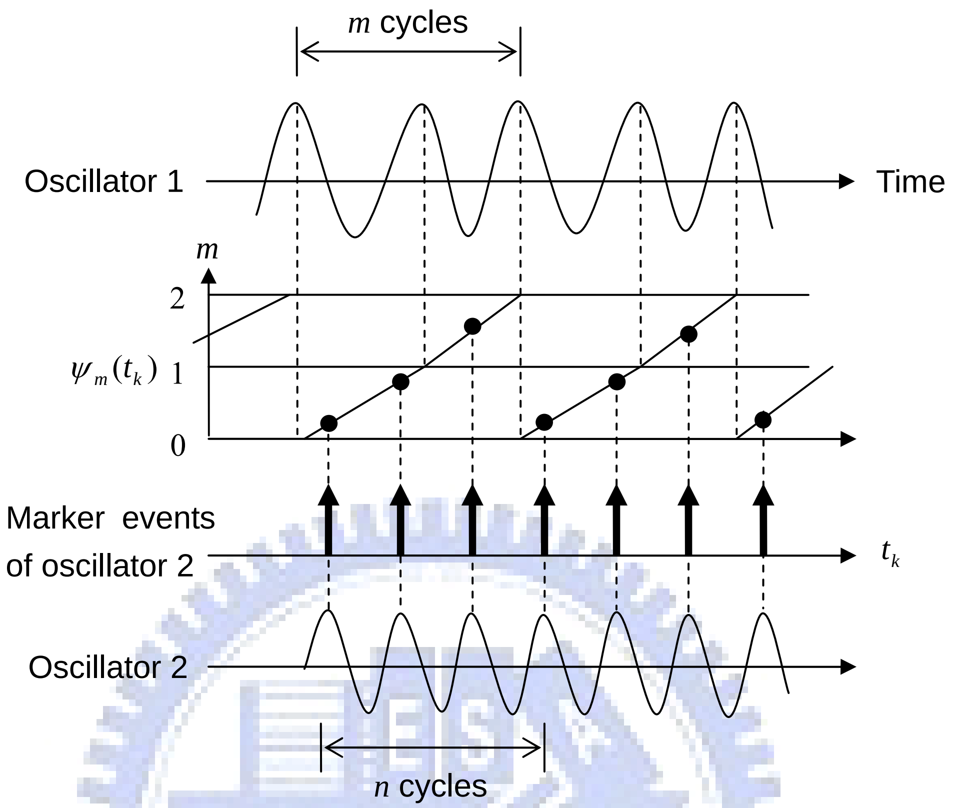


Figure 4-1. Illustration of the synchrogram construction.

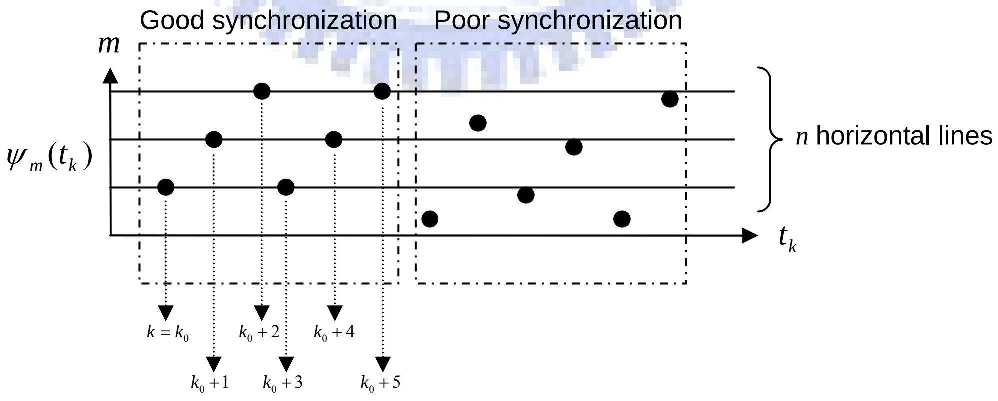


Figure 4-2. Examples of good synchronization and poor synchronization.

4.3 Experimental setup

4.3.1 Subjects

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 to their participation in the study.

4.3.2 Procedure

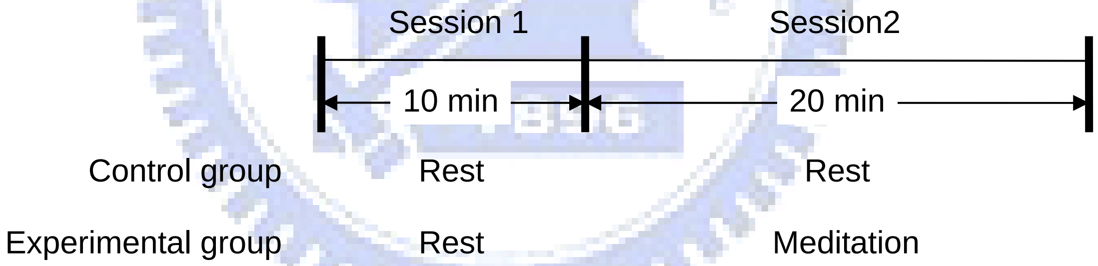


Figure 4-3. Experimental procedure.

The experiments comprised two sessions (Fig. 4-3). 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, subjects in the control group continued resting for 20 min; meanwhile, experimental group 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.

4.3.3 Signal acquisition

The ECG and respiration signals were recorded simultaneously at 1000 Hz sampling rate using PowerLab/16SP recording system (ADInstruments, Sydney, Australia; see Fig. 3-7 in section 3.3.3). Furthermore, the ECG signal was pre-filtered by a 0.3-200 Hz bandpass filter, and the respiratory signal was pre-filtered by a lowpass filter with cutoff frequency of 5 Hz. A 60-Hz notch filter was applied to remove artifacts from power line or the surroundings.

The ECG signal was recorded using Lead I of standard bipolar limb leads (see Fig. 3-8 in section 3.3.3). Electrode site on the left (right) arm was connected to the amplifier’s positive (negative) input, with the ground on the inside of left ankle. The disposable ECG electrodes (Medi-Trace 200 Foam Electrodes, Kendall, Chicopee, MA, USA; see Fig. 3-9(a) in section 3.3.3) were applied in the experiments. The respiratory signal was recorded using a piezo-electric transducer (Model 1132 Pneumotrace II (R), UFI, Morro Bay, CA, USA; see Fig. 3-9(b) in section 3.3.3), wrapped around the belly covering the navel.

4.4 Phase synchronization analysis

This study employs the synchrogram method introduced in Section 4.2.2 to analyze the phase synchronization between cardiac and respiratory systems. The flowchart of CRPS analysis is shown in Fig. 4-4.

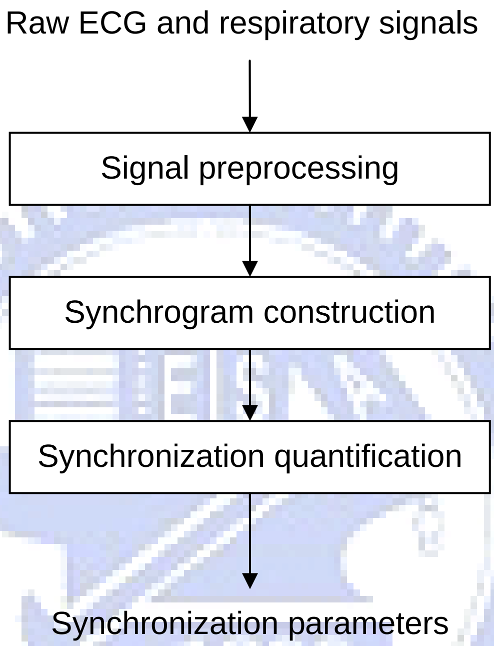


Figure 4-4. Flowchart of cardiorespiratory phase synchronization analysis.

4.4.1 Signal preprocessing

The frequency bands of ECG QRS complexes and respiratory signals are approximately 10–30 Hz (Kadambe *et al.* 1999; Köhler *et al.* 2002) and 0.15–0.4 Hz, respectively. Accordingly, in the preprocessing stage, the ECG and respiratory signals were downsampled to 200 Hz to conserve computational resources. The R peaks of the ECG signal and the inspiration-phase peaks of the respiratory signal were then detected automatically and reviewed manually.

4.4.2 Cardiorespiratory synchrogram construction

The first step to construct the cardiorespiratory synchrogram is to calculate the instantaneous phase of the respiratory signal. This study employed a method based on marker events to characterize the cyclic patterns of oscillators (Pikovsky *et al.* 2000). The marker events were determined from the inspiration-phase peaks of the respiratory signal. For each marker event, a phase increase of 2π was assigned and the instantaneous phase $\phi_r(t)$ at any time t was determined by linear interpolation (see Fig. 4-5). Subsequently, the *normalized relative phases* of heartbeats within m respiratory cycles were calculated

$$\psi_m(t_k) = \frac{1}{2\pi}\left[\phi_r(t_k) \bmod (2\pi m)\right], \tag{4-5}$$

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 '$\bmod (2\pi m)$' denotes wrapping the phase values into the interval $[0, 2\pi m)$ (i.e. m consecutive respiratory cycles are integrated into one longer cycle). The plot of $\psi_m(t_k)$ against t_k then construct the synchrogram.

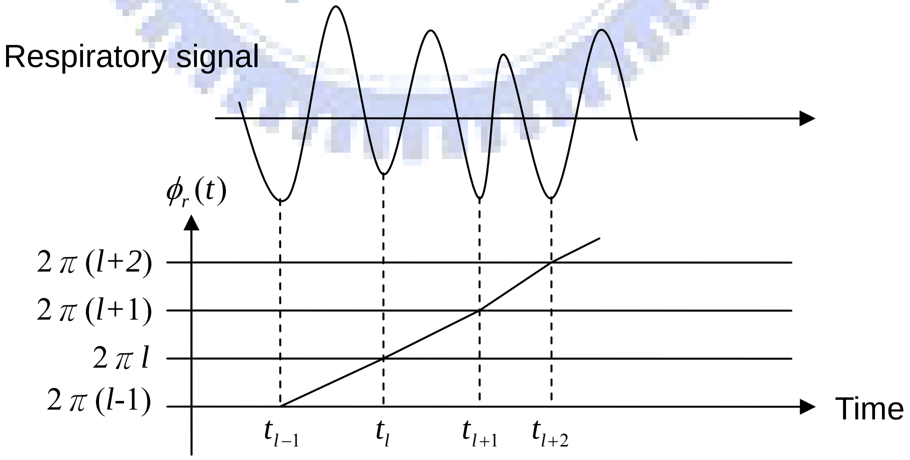


Figure 4-5. Determination of instantaneous phase using method based on marker events. In this example, the marker events are determined from the inspiration-phase peaks of the respiratory signal.

This study observed the CRPS within three respiratory cycles. Three synchrograms with $m = 1$, 2, and 3 thus were plotted for each subject. As an example, Fig. 4-6 displays the three synchrograms derived for an experimental subject during meditation. As introduced in section 4.2.2, $n : m$ phase synchronization will result in n horizontal lines in the synchrogram. Figure 4-6(a) presents the 4:1 synchronization between 11 and 18 min, resulting in four horizontal lines.

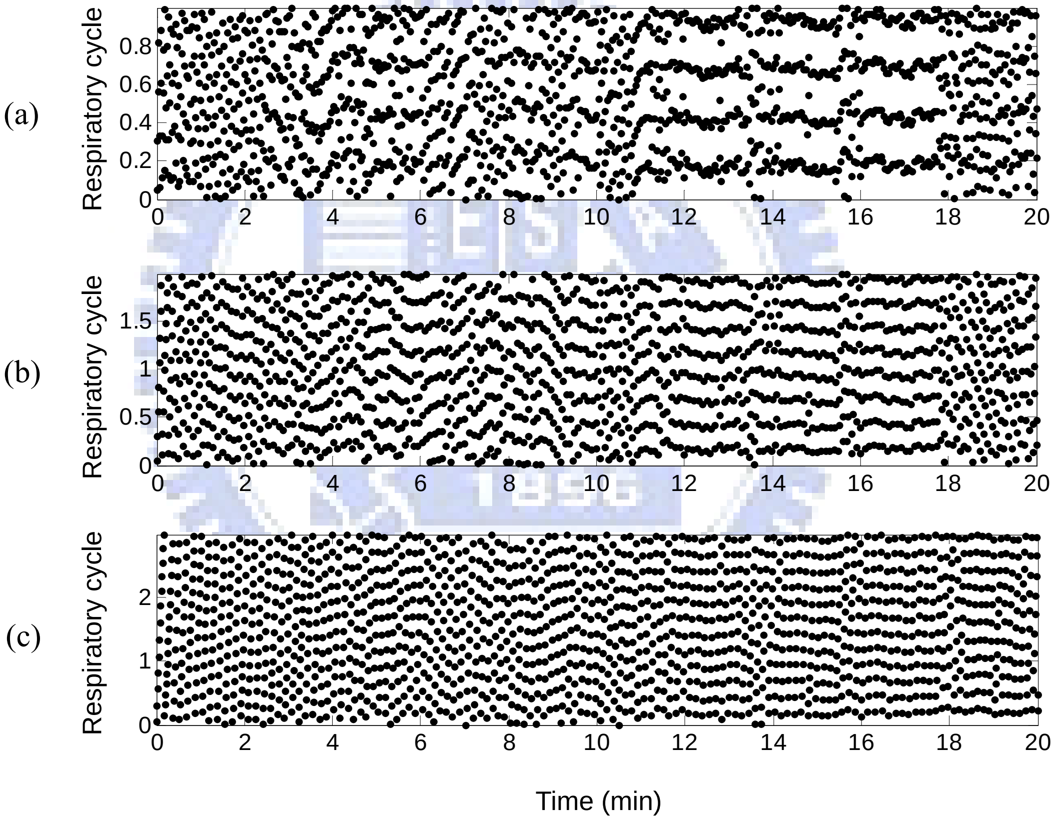


Figure 4-6. The cardiorespiratory synchrograms of experimental subject 1003 during meditation: (a) $n:1$ synchrogram (b) $n:2$ synchrogram (c) $n:3$ synchrogram. The $4:1$ synchronization is evidently observed at 11-18 min, showing four horizontal lines in the $n:1$ synchrogram.

4.4.3 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

$$\Psi_{n,m}(t_k) = \frac{2\pi}{m}\{[\psi_m(t_k)\cdot n] \bmod m\}. \tag{4-6}$$

Based on eq. (4-6), the n horizontal lines are merged into one horizontal line (see Fig. 4-7). 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

$$\gamma_{n,m} = \left\{\frac{1}{N}\sum_k \cos[\Psi_{n,m}(t_k)]\right\}^2 + \left\{\frac{1}{N}\sum_k \sin[\Psi_{n,m}(t_k)]\right\}^2, \tag{4-7}$$

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*). This study quantified the synchronization degree $\gamma_{n,m}$ using a one-minute window with moving step size of one R peak.

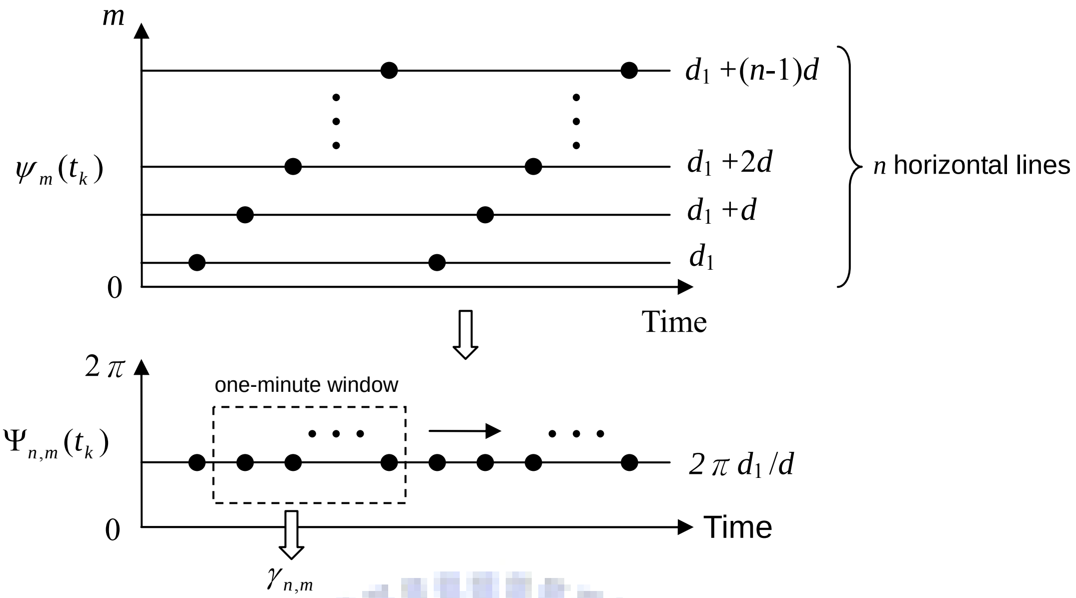


Figure 4-7. The process of quantifying the degree of synchronization: an example of complete $n:m$ synchronization.

To determine all possible pairs of (n,m), instantaneous frequency ratio f_h/f_r was first calculated, where f_h denotes the instantaneous frequency of heart beat and f_r represents the instantaneous frequency of respiration. The maximum and minimum values of frequency ratio, $min[f_h/f_r]$ and $max[f_h/f_r]$, were then applied as the bounds of (n,m) pairs: $min[f_h/f_r] \le n/m \le max[f_h/f_r]$. Figure 4-8(a) illustrates the time-varying synchronization degrees $\gamma_{n,m}(t_k)$ 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 $\gamma_{\max}(t_k)$. Figure 4-8(b) shows the sequence $\gamma_{\max}(t_k)$ extracted from $\gamma_{n,m}(t_k)$ of Fig. 4-8(a).

To identify the periods of significant synchronization in a relative sense, we set a threshold α 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*. To determine the value of α, values of $\gamma_{\max}(t_k)$ of each subject were averaged using a one-minute window size without overlap and the resulting mean values were denoted by γ_{mean}. Histograms of γ_{mean} were then presented for both groups (see Fig. 4-9). Clearly, 90% of the values were below 0.2. Therefore, the threshold of α =0.2 could be a moderate choice.

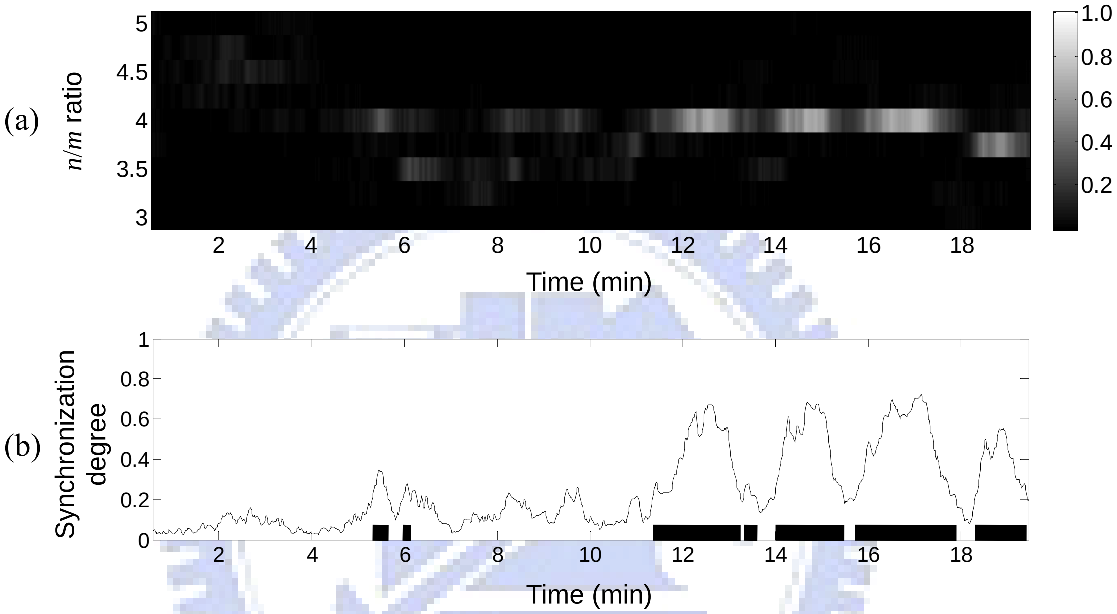


Figure 4-8. Synchronization degree of experimental subject 1003 during meditation: (a) Time-varying synchronization degrees $\gamma_{n,m}(t_k)$ for all possible (n,m) pairs. The right color bar denotes the scale mapping for color representation. The map clearly illustrates the transition of synchronization 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.

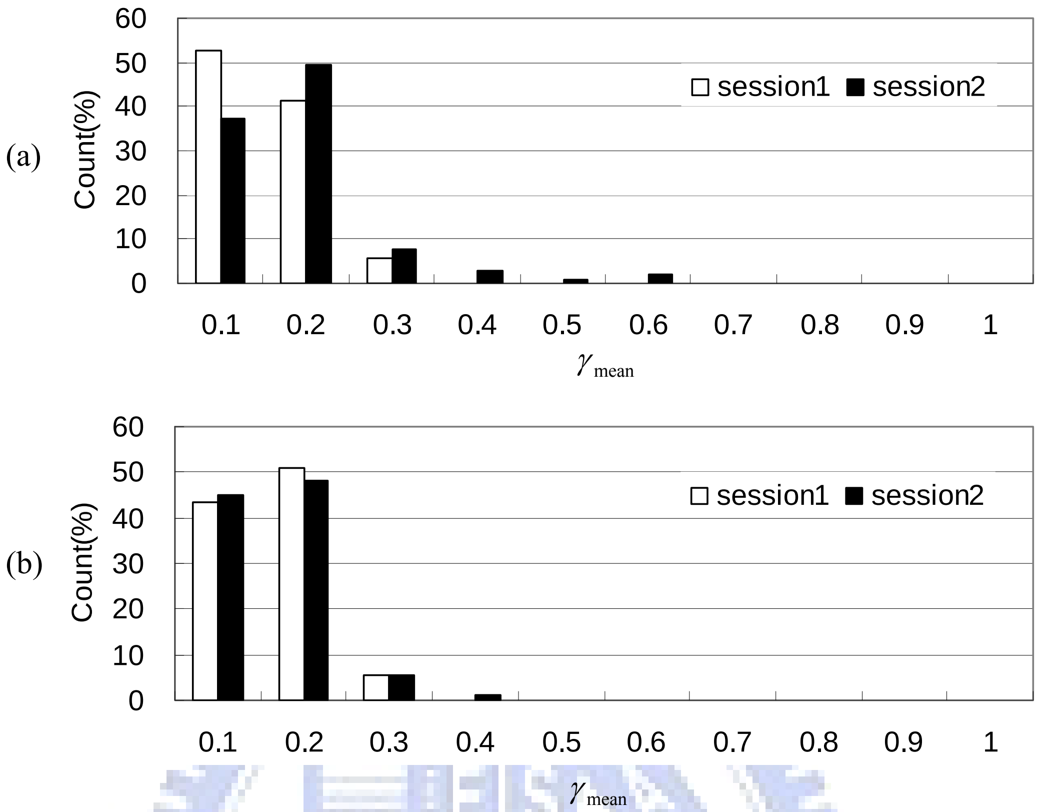


Figure 4-9. Histograms of γ_{mean} for (a) the experimental group and (b) the control group.

4.4.4 Measured parameters

The frequency ratio and three synchronization parameters (lasting length, number of epochs, and total length) were measured and analyzed 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 (epochs/10 min): Number of significant synchronization epochs per ten minutes (the normalization in time was used because of the different lengths of the two experimental sessions);

(3) Total length (s/10 min): Total durations of all significant synchronization epochs in ten minutes.

4.5 Statistical analysis

SPSS (version 12.0 for Windows) was used for the statistical analysis. Two-way ANOVA (2 groups × 2 sessions) with repeated measures was used to assess the statistical differences between the two groups and the two sessions for each variable. Two main effects (group and session) and an interaction effect (group × session) were verified. When two-way ANOVA revealed significant interaction, we performed simple effects analysis for each group and session. The level of statistical significance was set at 0.05, and comparisons were two tailed.

Pearson's correlation coefficient was used to investigate the correlation between synchronization degree and three variables (heart rate, respiration rate and frequency ratio). The level of statistical significance was set at 0.05, and the tests were two tailed.

4.6 Results

4.6.1 Heart rate and respiration rate

Table 4-1 lists the mean values of heart rate and respiration rate for each group in different sessions. Two-way ANOVA analysis revealed neither significant main effect nor significant interaction effect for mean respiration rate. Furthermore, significant interaction (group × session) effects were observed for mean heart rate [$F(1,14)=13.47$, $p=0.003$]. Further test of simple effects revealed a significant increase of mean heart rate for experimental subjects in Session 2 compared to Session 1 [$F(1,14)=14.59$, $p=0.002$], but no significant difference for the control subjects. Furthermore, experimental subjects exhibited significantly higher mean heart rate than control subjects during Session 2 [$F(1,28)=8.76$, $p=0.006$]. The Pearson's correlation coefficient showed no significant correlation between synchronization degree and heart rate [r=0.089, df=480, $p=0.052$], but did display significant correlation between synchronization degree and respiration rate [r=0.155, df=480, $p=0.001$].

4.6.2 Frequency ratio

Table 4-1 lists the mean values of frequency ratio for each group in different sessions. Two-way ANOVA analysis revealed neither significant main effect nor significant interaction effect for the frequency ratio. Meanwhile, Pearson's correlation coefficient showed no significant correlation between synchronization degree and frequency ratio [r=-0.061, df=480, *p*=0.186]. Figure 4-10 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.

Table 4-1. Heart rate, respiration rate and frequency ratio 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
Heart rate (beats/min)	67.6±7.3	66.0±6.6	70.4±8.1	76.3±5.4	NS	NS	0.003*
Respiration rate (breaths/min)	16.6±1.7	16.8±1.8	15.8±1.5	15.9±2.4	NS	NS	NS
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

Values are means±SD. NS = not significant; *Significant difference (*p*<0.05).

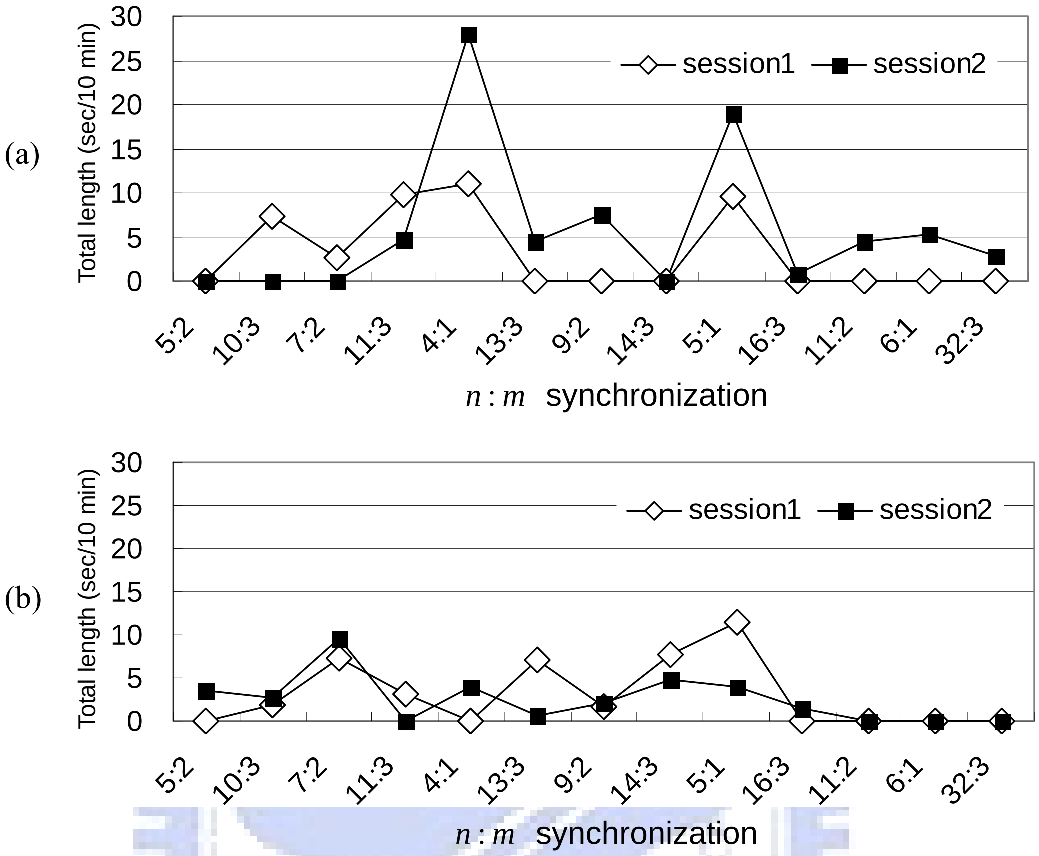


Figure 4-10. The average total length of significant synchronization epochs at different $n:m$ for (a) the experimental group and (b) the control group.

4.6.3 Lasting length of synchronization

Figure 4-11 shows the histograms of the lasting length of synchronization for both groups. The figure shows that most synchronization epochs were shorter than 30 seconds for both groups. Long synchronization with epoch length > 90 s was rare, and only observed during meditation (4:1 synchronization lasting for 114 s and 131 s). Based on the results of statistical analysis, Table 4-2 reveals neither significant main effect nor interaction effect for the lasting length of synchronization. This indicates that, in general, neither meditation nor rest significantly affected the lasting length of synchronization.

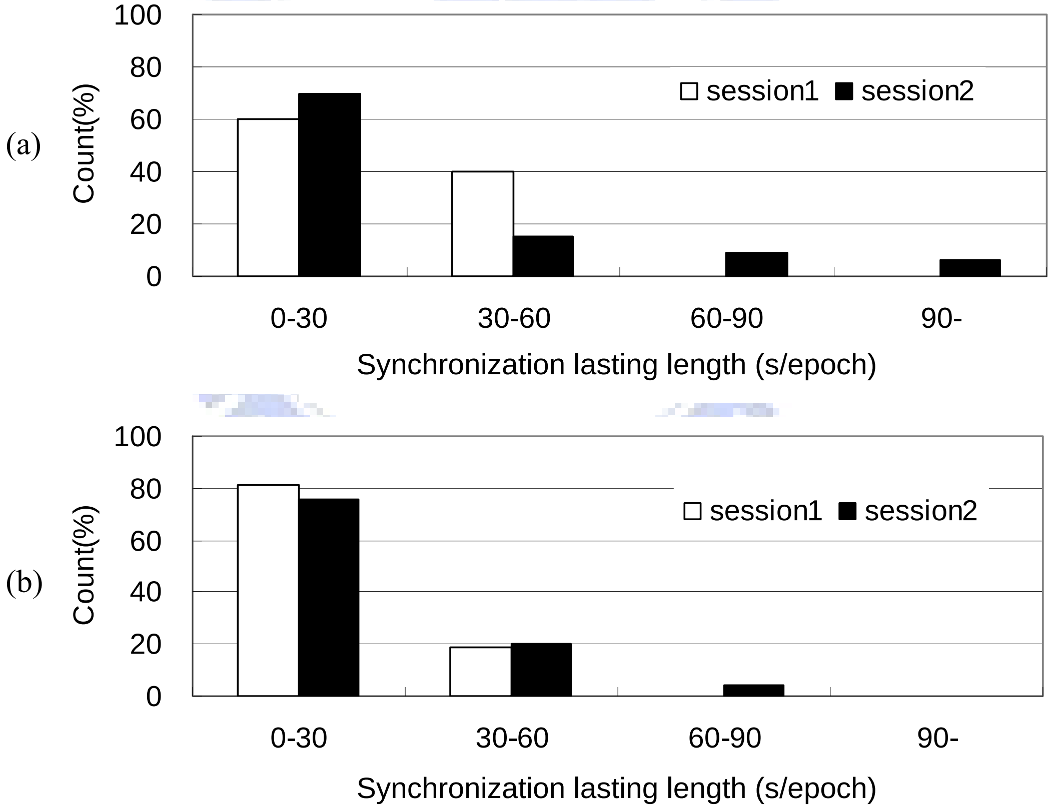


Figure 4-11. Histograms of the lasting length of significant synchronization epochs for (a) the experimental group and (b) the control group.

Table 4-2. The values of 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
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 (epochs/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 ($p<0.05$).

4.6.4 Number of synchronization epochs

Table 4-2 reveals significant interaction (group × session) effects for number of epochs [$F(1,14)=7.30$, $p=0.017$]. Further test of simple effects revealed a significant increase in number of epochs for experimental subjects from Session 1 to 2 [$F(1,14)=6.45$, $p=0.024$], but no significant difference for the control subjects.

4.6.5 Total length of synchronization

Table 4-2 indicates significant interaction (group × session) effects for total length [$F(1,14)=4.67$, $p=0.048$]. Further test of simple effects indicated a significant increase in total length for experimental subjects from Session 1 to 2 [$F(1,14)=5.49$, $p=0.034$], but no significant difference for the control subjects. Furthermore, experimental subjects exhibited significantly longer length of synchronization than control subjects during Session 2 [$F(1,28)=5.75$, $p=0.023$].

Chapter 5－

Discussion and Conclusion

To explore the efficacy of Chan meditation on stress manipulation, we have developed a number of researches based on various physiological and psychological parameters. This dissertation mainly reports the results of studying cardiovascular and respiratory systems and the interaction of two systems. In addition, paper survey based on well-developed questionnaire (DASS) was conducted and presented in the dissertation. Subjects of the study included Chan meditators (experimental subjects) and non-meditators (control subjects). The following Sections discuss the results and summarize the effects of Chan meditation. Finally, Section 5.5 describes some issues left for further study in the future.

5.1 Investigation of meditation effects on perceived stress

The results of the study on perceived stress may be summarized as follows. First, the college students in Taiwan present higher percentage of population in the negative-emotion problems as compared with the results of normative data survey by Crawford and Henry (2003). Second, the college students with Chan-meditation practice in daily lives present much lower percentage of population in the negative-emotion problems than those without Chan meditation practice in our surveyed pool. Third, more meditation experience, longer meditation duration, and higher meditation frequency will promote the meditation effectiveness on reducing the negative-emotion problems.

Such high percentage of Taiwan college students with negative-emotion problems shows the need for emotion management or stress manipulation methods on campus. Students who practice Chan meditation in daily lives can well relax through smoothly abdominal breathing and guarding some important spots (Chakras) inside the body, that allow the stress or negative emotions to be reduced or even released. However, one result of this study presented that short-term meditation practices were not significantly effective in reducing depression and anxiety levels. This phenomenon was also reported by Winzelberg and Luskin (1999) in anxiety reduction. With a larger pool of meditation practitioners, we further found that meditation experience of at least one-half year was suggested for attaining significant efficacy in reducing depression and anxiety levels. This fact indicates that, in comparison with tension/stress, depression and anxiety are more difficult to be manipulated. And in such situation, meditation experience becomes essential to effectively manipulate depression and anxiety.

One limitation of this survey study was the difficulty in manipulating the background conditions of the two groups due to the original design of involving a large pool of college students. In such case, an explicit merit is to obtain the results of statistical significance based on a more general, wide-scope survey. On the other hand, it would possibly result in such inter-group biases like personality, stressors, etc. However, significant effects of meditation were demonstrated by the intra-group analyses for the meditation practitioners.

5.2 Heart rate variability in Chan meditation

In the study of HRV, we observed several segments of regular oscillations in heart rate signals during inward-attention meditation. Similar regular oscillations were also observed in previous meditation studies (Lehrer *et al.* 1999; Peng *et al.* 1999; Peng *et al.* 2004; Cysarz and Büssing 2005). Tiller *et al.* (1996) called it the “entrainment mode” of heart function which can be induced under positive emotions. In these pervious studies, such regular oscillations all appeared in the low-frequency (LF) band of HRV due to the slow breathing. Our study showed that such regular oscillations could also appear in the high-frequency (HF) band of HRV but with smaller amplitude. Furthermore, such regular oscillations were observed particularly at the low LF/HF ratio, that might suggest the sympathovagal balance as a key role in the occurrence of this regular oscillations. That is, when the autonomous nervous system is under parasympathetic predominance, the heart rate can be purely modulated by respiration and reveals a regular heart rate signal.

The results of two-way ANOVA analysis showed significant differences in several HRV parameters. Those indicated that there existed both common and different effects between inward-attention meditation and normal rest on heart rate variability. In respect of time-domain HRV parameters, neither inward-attention nor normal rest had effects on RMSSD. Otherwise, normal rest had a significant effect of increasing the SDNN and inward-attention meditation had a significant effect of increasing the Mean HR. For frequency-domain HRV parameters, inward-attention and normal rest had the common effects of increasing the LF power and HF power. The different effects included decreases of the LF/HF ratio and LF norm as well as increase of HF norm during inward-attention meditation, which suggested a sympathovagal balance toward parasympathetic activity (Eckberg 1997) and reflected a certain state of relaxation. As regards the normal rest, there appeared no significant effect on LF norm, HF norm and LF/HF ratio. In the previous meditation study by Takahashi *et al.* (2005), the results showed that the decrease of LF/HF ratio and LF norm were correlated to the increase of slow alpha power in the frontal cortical region which reflected enhancement of inward attention. Accordingly, the inhibitory effect on sympathetic activity (decrease in LF/HF ratio and LF norm) during meditation may be caused by the enhancement of inward attention.

In conclusion, inward-attention meditation practice appears to push the sympathovagal balance to parasympathetic predominance and induce regular oscillations in heart rate. These results may support the health benefits of meditation in conditions where sympathovagal balance toward sympathetic activity due to stress or disease.

5.3 Cardiorespiratory phase synchronization of Chan-meditation practitioners

For the synchronization degrees quantified from the synchrogram, no standard criterion exists for firmly identifying their significance. This study established the criterion in a relative, statistical sense based on the histograms of γ_{mean}. Comparison between Fig. 4-8(b) and Fig. 4-6 has shown that the epochs of significant synchronization in Fig. 4-8(b) were temporally well aligned with those parallel lines in Fig. 4-6. It thus justifies the feasibility of the criterion proposed in this study.

To explore whether the heart rate, respiration rate and frequency ratio affect synchronization degree, Pearson's correlation analysis was applied to examine the pairwise correlations. The result demonstrated that only respiration rate was significantly (but slightly) correlated with synchronization degree. Accordingly, we might suggest that synchronization degree is independent of heart rate and frequency ratio. Meanwhile, the respiration rate, despite being significantly correlated with synchronization degree, did not differ significantly between groups and between sessions. Thus, the respiration-rate factor in studying CRPS could be ignored when making comparisons between groups and between sessions.

This study found that most synchronous epochs were short (< 30 s). Long synchronization with epoch length > 90 s was rare and only observed during meditation. Furthermore, a predominance of 4:1 and 5:1 synchronizations was observed in experimental subjects during meditation. In an earlier paper (Bartsch *et al.* 2007), similar predominance was reported under the state of non-REM sleep, primarily on 4:1 synchronization.

Furthermore, Stefanovska *et al.* (2000) 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 compared with the baseline period. Notably, the lasting length of synchronization did not 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.

According to previous studies, we suggest two factors that may play significant roles in enhancing CRPS during meditation: higher brain region and baroreflex sensitivity. Bartsch *et al.* (2007) suggested that the influence of higher brain regions on autonomic nervous system (ANS) could affect the CRPS. Their work found suppression of phase synchronization during REM sleep in which the influence of higher brain regions on ANS increased. In contrast, CRPS was enhanced during non-REM sleep in which the effect of higher brain regions on ANS was smaller. In our study, the meditators concentrated their mind on the chakra. This technique of inwards attention can help subjects release themselves from wild and uncontrollable thoughts and achieve a transcendental-consciousness state. The interference of higher brain regions on ANS may thus be reduced and the CRPS enhanced.

A modeling-based study by Kotani *et al.* (2002) found that sympathetic baroreflex sensitivity can affect the occurrence of CRPS. As the baroreflex sensitivity of sympathetic nerves increases, the region (Arnold tongues) (Schäfer *et al.* 1999) of CRPS grows, causing more frequent synchronization. In the study of Takahashi *et al.* (2005), inhibition of sympathetic activity was observed in subjects during meditation. Since the inhibition of sympathetic activity can be resulted from the increase of sympathetic baroreflex sensitivity (Kotani *et al.* 2002), it is rational to hypothesize that baroreflex sensitivity accounts for the enhancement of CRPS during meditation and worth to be studied in the future.

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. Furthermore, the emergence of CRPS can be considered an indicator of good coordination or efficient co-action between cardiac and respiratory systems.

5.4 Summary

This dissertation was aimed to investigate the efficacy of Chan meditation in stress release. A survey study and two experimental-protocol studies were performed to study both the psychological and physiological aspects of stress syndromes.

For the psychological aspects, the results showed that, (1) considerably high percentage of college students who did not practice Chan meditation exhibited negative emotional problem (Depression: 45%; Anxiety: 48%; Stress/Tension: 50%); (2) much lower percentage of students with meditation practice encountered the negative emotional problem (Depression: 8%; Anxiety: 30%; Stress/Tension: 12%), manifesting the benefits of meditation on stress manipulation; (3) more meditation experience, longer meditation duration, and higher meditation frequency could further improve the states of negative emotion; and (4) meditation experience played a considerable role in effectively manipulating some stress symptoms like depression and anxiety, demonstrated by significantly lower scores ($p<0.001$) in the group of experienced (>0.5year) meditators as compared with the control group.

For the physiological aspects, the results revealed both common and different effects on

HRV between inward-attention meditation and normal rest. The major difference of effects between two groups were the decrease of LF/HF ratio and LF norm as well as the increase of HF norm, which suggested the benefit of a sympathovagal balance toward parasympathetic activity. Moreover, we observed regular oscillating rhythms of the heart rate when the LF/HF ratio was small under meditation. According to previous studies, regular oscillations of heart rate signal usually appeared in the low-frequency band of HRV under slow breathing. Our findings showed that such regular oscillations could also appear in the high-frequency band of HRV but with smaller amplitude.

In the study of CRPS, the results showed that normal rest resulted in much weaker CRPS. Statistical analysis reveals that the number of synchronous epochs and the total synchronization length significantly increase (p=0.024 and 0.034 respectively) during meditation. Furthermore, a predominance of 4:1 and 5:1 rhythm-ratio synchronizations was observed during meditation. Consequently, we conclude that CRPS can be enhanced during meditation, and reveals a predominance of specific frequency ratios.

In conclusion, Chan meditation practice can reduce the negative emotions (depression, anxiety, and stress/tension), increase the parasympathetic activity, induce regular heart rate oscillations, and enhance the CRPS. These findings provided the evidence that Chan meditation practice can manipulate both the psychological and physiological aspects of stress syndromes.

5.5 Future work

In the study of CPRS, baroreflex sensitivity is considered a possible factor enhancing the CPRS during meditation. Baroreflex is responsible for controlling of blood pressure. High baroreflex sensitivity indicates better control of blood pressure, while low baroreflex sensitivity is correlated with several diseases (Carlson *et al.* 1996; Mancia *et al.* 1997; La Rovere *et al.* 1998; Lefrandt *et al.* 1999; Lantelme *et al.* 2002). Various interventions were proposed to improve the baroreflex sensitivity (Reyes del Paso 1999; Bernardi *et al.* 2002; La Rovere *et al.* 2002). Therefore it is interesting to study the effects of meditation on baroreflex sensitivity and the relation between baroreflex sensitivity and CRPS during meditation.

Besides, it has been reported in the literatures that HRV and CPRS might be related to the central neural regulation (Takahashi *et al.* 2005; Bartsch *et al.* 2007). In our studies, the meditation with inward-attention was found to increase the parasympathetic activity, induce regular heart rate oscillations, and enhance the CRPS that has been best observed under low cognition. These findings raise the possibility of certain interactions between brain and cardiac/cardiorespiratory system during inward-attention meditation. Hence, for profound understanding of the Chan-meditation process and effects, EEG signals could be included to explore the mutual interaction between the brain and cardiac/cardiorespiratory system.

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Appendix A－

Categories of CAM

The National Center for Complementary and Alternative Medicine (NCCAM), one institute of the National Institutes of Health (NIH) of American, classified the CAM into five categories: (1) whole medical system, (2) mind-body medicine, (3) biologically based practices, (4) manipulative and body-based practices, and (5) energy medicine. The corresponding information can be searched on its website http://nccam.nih.gov.

Appendix B－
Chan-Buddhist Meditation

Chan-Buddhist meditation is a unique meditation practice of Orthodox Chan Buddhism which originated from the affair that Buddha Shakyamuni transmitted this light of wisdom to the Great Kashiyapa some 2,500 years ago. The same path towards Buddhahood was promulgated to mainland China in 527 by Bodhidharma, the 28th patriarch. The current patriarch is Chan master Wu Chueh Miao Tien, the 85th patriarch of the orthodox Chan-Buddhism Sect, in Taiwan.

Appendix C－

DASS Questionnaire Sheet

DASS 量表

填表日期：西元　　　年　　月　　日

第一部份、個人基本資料：

◎姓名：

◎性別：□男 □女

◎出生：(西元)　　　年

◎學校：　　　　　　　　科系 ：

◎年級：□大一 □大二 □大三 □大四 □碩一 □碩二 □博士　　年級

◎E-mail：

-----以下為禪定組才需填寫--

◎開始禪修：(西元)　　　年　　月

◎平常禪坐時間：　　分鐘(採□單盤□雙盤)

◎過去一個月來，平均每週禪定次數：　　次

第二部份、請您依自己「平常」生活中的實際感受，在適當的□內打勾。答案沒有對錯，不必在每一題上花太多的時間：

	3 總是如此	2 常常如此	1 有時如此	0 從未如此
1. 我發覺自己為很細微的事而煩惱	□	□	□	□
2. 我感到口乾	□	□	□	□
3. 我好像不能再有愉快、舒暢的感覺	□	□	□	□
4. 我感到呼吸有困難（例如:呼吸過促、氣喘）	□	□	□	□
5. 我真的好像提不起勁	□	□	□	□
6. 我對事情往往作出過度反應	□	□	□	□
7. 我感到身體搖晃不穩（例如:有腳軟的感覺）	□	□	□	□
8. 我感到很難放鬆自己	□	□	□	□
9. 某些場合讓我感到焦慮，極渴望立刻離開，鬆一口氣	□	□	□	□

	3 總是如此	2 常常如此	1 有時如此	0 從未如此
10. 我覺得自己沒有甚麼可盼望的將來	□	□	□	□
11. 我發覺自己很容易感到不快	□	□	□	□
12. 我覺得自己消耗很多精神	□	□	□	□
13. 我感到憂愁悲哀	□	□	□	□
14. 若受到阻延（例如交通擠塞），我會感到很不耐煩	□	□	□	□
15. 我有暈眩的感覺	□	□	□	□
16. 我感到對所有事情都失去興趣	□	□	□	□
17. 我覺得自己不怎麼配做人	□	□	□	□
18. 我發覺自己很容易被觸怒	□	□	□	□
19. 我無故流汗（例如:手腳冒汗）	□	□	□	□
20. 我無緣無故地感到害怕	□	□	□	□
21. 我感到生命沒有價值	□	□	□	□
22. 我覺得很難讓自己安靜下來	□	□	□	□
23. 我感到吞嚥困難	□	□	□	□
24. 我覺得不能從所作的事情中獲得樂趣	□	□	□	□
25. 我平時也感覺到心跳或心律不正常	□	□	□	□
26. 我感到憂鬱沮喪	□	□	□	□
27. 我感到自己很容易煩躁	□	□	□	□
28. 我感到快要恐慌了	□	□	□	□
29. 受了刺激後，我感到很難去平撫自己	□	□	□	□
30. 我害怕被一些瑣碎而不熟悉的事情難倒	□	□	□	□
31. 我對任何事都無法熱衷	□	□	□	□
32. 我很難忍受工作時的障礙	□	□	□	□
33. 我神經緊張	□	□	□	□
34. 我覺得自己很沒有價值	□	□	□	□
35. 我無法容忍那阻礙我繼續工作的事情	□	□	□	□
36. 我感到驚惶	□	□	□	□
37. 我對未來完全失去希望	□	□	□	□
38. 我感到生命毫無意義	□	□	□	□
39. 我感到忐忑不安	□	□	□	□
40. 我憂慮一些令自己恐慌或出醜的場合	□	□	□	□
41. 我感到顫抖（例如手震）	□	□	□	□
42. 我感到很難去開始工作	□	□	□	□

-----------------結束，請檢查有沒有漏填的地方----------------

Table C-1. Three sets of items in DASS questionnaire corresponding to different negative emotions, depression, anxiety, and stress/tension

Negative emotion	Items in questionnaire
Depression	3, 5, 10, 13, 16, 17, 21, 24, 26, 31, 34, 37, 38, 42
Anxiety	2, 4, 7, 9, 15, 19, 20, 23, 25, 28, 30, 36, 40, 41
Stress	1, 6, 8, 11, 12, 14, 18, 22, 27, 29, 32, 33, 35, 39

Table C-2. Five ranges of intensity for each negative emotion state (depression, anxiety, and stress/tension) in DASS

	Depression	Anxiety	Stress
Normal	0-9	0-7	0-14
Mild	10-13	8-9	15-18
Moderate	14-20	10-14	19-25
Severe	21-27	15-19	26-33
Extremely Severe	28-42	20-42	34-42

Appendix D─ R-Peaks Detection of ECG

The flowchart of R-peaks detection is shown below.

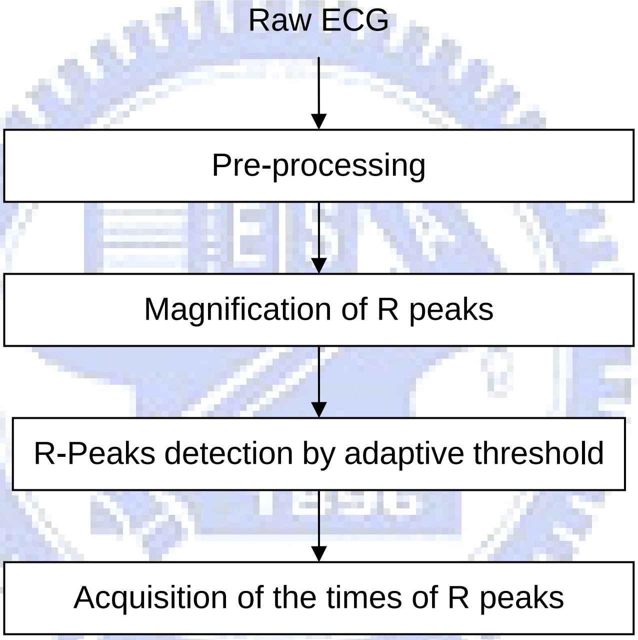

Figure D-1. Flowchart for R-peak detection.

Step 1. ECG signal pre-processing

Power spectrum of the QRS complexes of an ECG signal is distributed mainly in the range of 10-30 Hz (Kadambe *et al.* 1999; Köhler *et al.* 2002). Accordingly, in pre-processing stage, we applied Matlab’s built-in polyphase filter scheme, including anti-aliasing (lowpass) FIR filter, to down-sample the raw ECG signal to the rate of 200 samples per second. The

ECG signal after down-sampling was then filtered by a 10-30 Hz bandpass filter to reduce the baseline drift and high frequency noises (for example, 60Hz power line noise and EMG signal) as well as to further enhance quality of the R peaks.

Step 2. Magnification of R peaks

R peaks were magnified by multiplying the pre-processed ECG signal $x(n)$ by its absolute-valued signal $|x(n)|$ to generate an R-magnified signal $x'(n) = x(n) \times |x(n)|$. As shown in Fig. D-2, the ECG signal before and after preprocessing is presented. Note that the amplitudes of R peaks are obviously enhanced and cleansed.

Step 3. R-Peaks detection by adaptive threshold

The threshold for R-peaks detection was determined for every one-minute frame, as the value of 0.3 times of the maximum ECG amplitude within the frame. Adaptive-threshold scheme was adopted for the reason that the range of ECG amplitude varies among subjects. Moreover, inter-subject variations are often inevitable in biomedical signals.

Step 5. Acquisition of the times of R peaks

For each QRS complex, there will exhibit a time duration that its amplitude bigger than the threshold as shown in Fig. D-3. The maximum amplitude during this time duration was determined, and its time position was employed as the time of R peak.

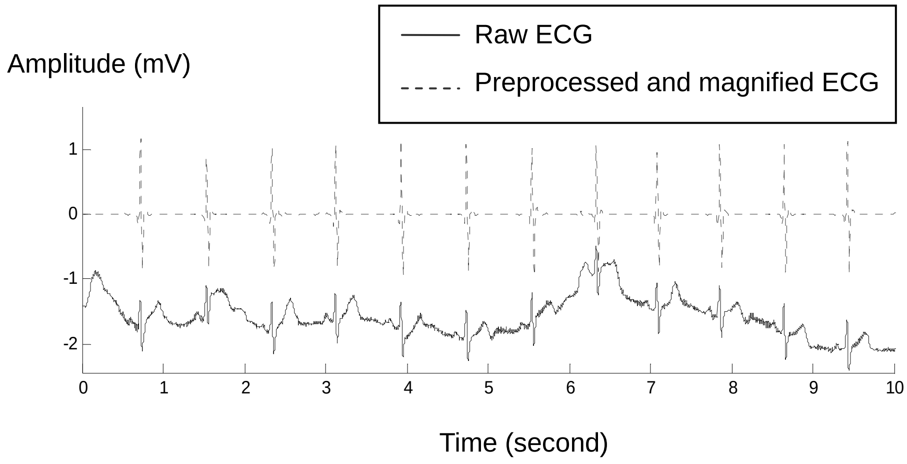

Figure D-2. The raw ECG and preprocessed ECG.

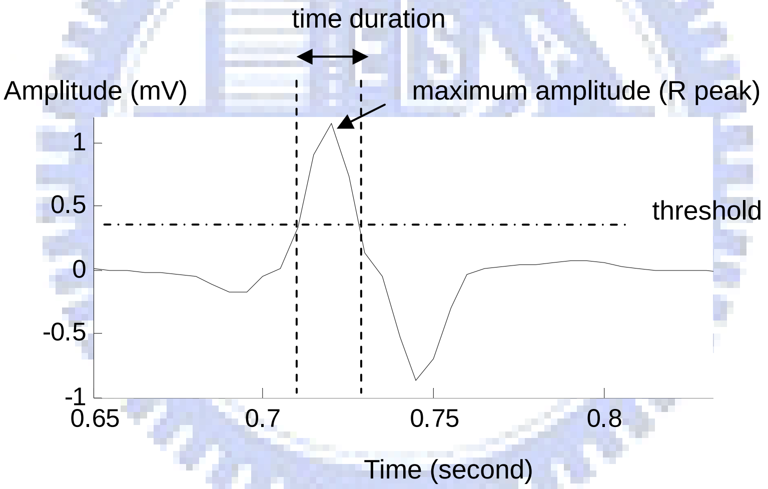

Figure D-3. R-peaks detection by threshold.

Vita and Publication List

Shr-Da Wu received his B.S. and Ph.D. degrees in Electrical and Control Engineering from National Chiao-Tung University, Taiwan in 1999 and 2009.

Journal:

[1] Lo PC and Wu SD, "Effect of Zen meditation practice on perceived stress in college students: a survey study," *Biomedical Engineering: Applications, Basis and Communications*, vol. 19, no. 6, pp. 1–5, 2007.

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