# 行政院國家科學委員會專題研究計畫 成果報告

## 禪坐之心肺交互作用與解壓研究
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# 行政院國家科學委員會補助專題研究計畫

## 禪坐之心肺交互作用與解壓研究

## Research on Cardiorespiratory Interaction and Stress-Relief Effect of Chan Meditation

**■成果報告**
**□期中進度報告**

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計畫主持人：羅佩禎
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# 行政院國家科學委員會專題研究計畫成果報告

禪坐之心肺交互作用與解壓研究

Research on Cardiorespiratory Interaction and Stress-Relief Effect of Chan Meditation

計畫編號： NSC 98－2221－E－009－100－

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主 持 人： 羅佩禎，國立交通大學 電機工程學系

## 中文摘要

諸多報導顯示，1980 年以來壓力相關症候受害者遽增；因此，禪坐在二十餘年前已成為最受重視並廣為採用之舒壓養生方法之一，大多數修練者都可以驗證禪坐之於舒解壓力的效能。本研究主要目的即經由心肺交互現象來探索其內在機制。

學界對於人類心血管循環系統與呼吸系統相互間的影響，已研究長達數十年；之間發現這兩個系統並非獨立運作。如RSA（呼吸對心率進行調頻作用）即為眾所周知的心肺交互現象。RSA 陳述心率變異與呼吸同步的情形，即，吸氣時心率增加、吐氣時心率下降，因此人類的肺部可進行高效能的空氣交換。除了調頻現象，同步特性和非線性之心肺交互作用，也成為研究焦點。

首先以Synchrogram analysis分析心肺相位同步現象，以bispectral analysis 探討心率與呼吸間之非線性偶合。結果顯示，禪坐時，同步發生率和發生時間長短都顯著增加，且兩種方法的結果有正相關。

禪坐中的調息已被證實其對於自律神經系統平衡有相當功效（由心率變異HRV 分析）。本研究結果顯示控制組在一定的呼吸控制之下（呼吸率為每分鐘十次），可出現顯著的心肺相位同步，而實驗組在禪坐時的相位同步和非線性交互作用則出現差異性極大的變化，CRPS和呼吸率之間並沒有特定關聯性。若觀察原始呼吸訊號，可發現禪坐者的呼吸率不像控制組（以電腦聲音調節其一呼一吸）那麼穩定，這是為何實驗組無法像控制組那樣容易達成好的CRPS，在進一步的研究後，發現禪坐若能進入較低且持續的呼吸率，可以有效引導出CRPS。

**關鍵字**：心肺交互作用、禪坐、壓力症候、心電圖、心率變異、自律神經系統、循環系統、呼吸系統、同步觀測分析、非線性交互作用、相位同步、腦電波。

# 英文摘要

It was reported that more people had been suffering the stress-related syndromes since 1980's. Chan meditation thus became one of the most important and widely adopted approaches for stress management and health enhancement some twenty-five years ago, The efficacy of Chan meditation in stress relief has been proved by most practitioners. This research is aimed to explore the inside mechanisms via the cardiorespiratory-interaction phenomenon.

The interaction between human cardiac and respiratory systems has been widely studied for many decades. It has been found that these two systems do not act independently; instead, they are coupled by some mechanisms. One well-known phenomenon of cardiorespiratory interaction is the frequency modulation of heart rate by respiration, which is known as respiratory sinus arrhythmia (RSA). RSA portrays the heart rate variability in synchrony with respiration, that is, the heart rate increases during inspiration and decreases during expiration. With RSA, human pulmonary air exchange can be more efficient. In addition to modulation, other cardiorespiratory interaction such as synchronization has been observed, and the nature of interaction like nonlinear coupling was proposed in recent years.

Firstly, Synchrogram analysis was applied to the investigation of phase synchronization, and time-phase bispectral analysis was employed in studying the nonlinear coupling. According to our results, number of the synchronous epochs, the total synchronization duration, and the number of the coupling epochs all significantly increased ($p=0.023$, 0.034, and 0.038, respectively) during meditation. As a result, the effect of meditation on cardiorespiratory synchronization was evident. Regarding the methodological coincidence between synchronization and nonlinear coupling, we found that positive correlation increased significantly ($p = 0.011$) during meditation. It suggests that under nonlinear coupling, meditation might enhance the phase synchronization between cardiac and respiratory systems.

Breathing regulation in Chan meditation has been demonstrated to be an effective approach for ANS (autonomic nerve system) balance accessed by HRV (heart rate variation). In our preliminary results, control subjects exhibited significant better degree of CRPS in the session of breathing control at the rate of 10 breaths/min. One the other hand, experimental group did not exhibit significant correlation between CRPS and respiratory rate. According to the time-dependent respiratory signal, meditation practitioners breathed in a free style during Chan meditation and thus could not keep a constant respiratory rate for a moderate duration. The experimental group thus did not achieve the state of CRPS as good as the control group even at the same respiratory rate of 10 breaths/min. We thus make a preliminary conclusion that a consistently slow respiration can induce an efficient CRPS.

Keywords: Cardiorespiratory interaction, Chan meditation, Stress syndrome, Electrocardiograph (ECG), Heart rate variation (HRV), Autonomic nerve system (ANS), Circulatory system, Respiratory system, Synchrogram analysis, Nonlinear coupling, Phase synchronization, Electroencephalograph (EEG).

# 1. INTRODUCTION

Meditation nowadays is widely acknowledged as one important technique in the category of mind-body medicine after having been proved to benefit human health and wellness in various aspects via the extensive, profound researches since 1960s and Meditation is described as a wakeful hypometabolic state of parasympathetic dominance that has been corroborated by such physiological indicators as the reduction of heart rate, blood pressure, and respiratory rate, significant increase in plasma melatonin levels and better regulation of cortisol level. As CAM (complementary and alternative medicine) becomes more popular in the West. Among a large variety of approaches in CAM, meditation has been one of the most widely acceptable practices due to its substantial effectiveness and safety. However, except for RSA phenomenon, very few researches are performed to study the synchronization and nonlinear coupling of cardiorespiratory systems during meditation. This study was aimed to investigate the phase synchronization and nonlinear coupling while cardiorespiratory interaction occurred during Chan meditation. Among various meditation techniques, Chan meditation originating from Dharma-Chan reveals an extraordinarily unique way of practicing meditation via “holy-heart unification” enlightenment. Our previous study on EEG (electroencephalograph) has revealed some exclusive characteristics of a Chan-enlightened brain.

The interaction between human cardiac and respiratory systems has been widely studied for many decades. It has been found that these two systems do not act independently; instead, they are coupled by some mechanisms. In addition to RSA (respiratory sinus arrhythmia) [1], other cardiorespiratory interaction such as synchronization has been observed, and the nature of interaction like nonlinear coupling was proposed in recent years [2-5].

In 1998, Schäfer et al. [2] applied the concept of phase synchronization of chaotic oscillators [6] to the development of a technique called ‘synchrogram’ to analyze irregular, non-stationary bivariate data. Afterward several researches followed the synchrogram method and presented the phenomenon of cardiorespiratory phase synchronization on different subjects. Duration and frequency ratio are parameters of phase synchronization that have ever been investigated in these researches. Cardiorespiratory phase synchronization (CPRS) is a recently investigated phenomenon reflecting certain type of interaction between cardiac and respiratory systems. According to previous studies, 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 and anesthesia, and was almost lost during physical strain. The transcendental consciousness state during meditation is a condition of low cognition level. According to previous studies, it may facilitate the appearance of CPRS.

In addition to synchronization, the nature of coupling between cardiac and respiratory systems has been investigated. In 2003, Jamšek et al. [7] proposed the time-phase bispectral analysis that introduced time dependence to the bispectral analysis of univariate data. In 2004, the method was used to detect the coupling phenomenon between cardiac and respiratory systems, and several episodes were detected (smaller than 2 minutes) [3].

Cardiorespiratory interaction has been identified as an important index of health condition and stress-management ability. Moreover, cardiorespiratory function can be assessed quantitatively by simultaneously recording ECG (electrocardiograph) and respiratory signals.

# 2. THEORY AND METHOD

The aim of this research was to investigate the phase synchronization and nonlinear coupling while cardiorespiratory interaction occurred during Chan meditation. Synchrogram analysis was applied to the investigation of phase synchronization, and time-phase bispectral analysis was employed in studying the nonlinear coupling. This study included 16 subjects, 7 experimental subjects with Chan-meditation experience and 9 control subjects in the same age range, yet, without any meditation experience.

## 2.1 The Synchrogram Method

### 2.1.1 Theory of Phase Synchronization

The phenomenon of synchronization is considered as an adjustment of rhythms, via specific manner of interaction, among distinctive self-sustained oscillators [4]. In classical sense of periodic self-sustained oscillators, synchronization is usually defined as locking (entrainment) of the phases,

$$\varphi_{n,m} = n\phi_1 - m\phi_2 = \text{const} \tag{2.1}$$

where $n$ and $m$ are integers, $\phi_1$ and $\phi_2$ are phases of two oscillators, and $\varphi_{n,m}$ is the generalized phase difference. Note that the values of $\phi_1$ and $\phi_2$ are not bounded in [0, 2$\pi$].

Follow the basic work of Stratonovich [8], phase locking in noisy systems is understood as the appearance of a peak in the distribution of the cyclic relative phase $\Psi_{n,m}$, and can be interpreted as the existence of a dominated stable value of phase difference between the two oscillators.

$$\Psi_{n,m} = \varphi_{n,m} \bmod 2\pi \tag{2.2}$$

where 'mod' is an operator converting the value of $\varphi_{n,m}$ into the range $[0, 2\pi]$ by subtracting $2\pi k$ ($k$ is an integer) such that $0 \le \Psi_{n,m} < 2\pi$.

### 2.1.2 Instantaneous Phase

The instantaneous phase at any time $t$ can be derived by the linear interpolation equation below,

$$\phi(t) = 2\pi \frac{t - t_k}{t_{k+1} - t_k} + 2\pi k \ , \ t_k \le t < t_{k+1} \tag{2.3}$$

where $t_k$ is the time of the $k^{th}$ marker event [9]. The instantaneous phase of $k^{th}$ marker event is $2\pi k$.

### 2.1.3 Synchrogram Method and Quantification

The synchrogram method [4] was used to analyze the phase synchronization of two interacting self-oscillatory systems. As described in equation (2.4), $\psi_m(t_{k_2})$ is obtained by wrapped phase $\phi_1$ modulo $2\pi m$, and is observed at time $t_{k_2}$ when the marker events of oscillator 2 occur. Then the values of $\psi_m(t_{k_2})$ at time $t_{k_2}$ are marked by dots along the vertical axis and the synchrogram is completed.

$$\psi_m(t_{k_2}) = \frac{1}{2\pi}[\phi_1(t_{k_2}) \bmod 2\pi m] \tag{2.4}$$

In the ideal case of $n$ : $m$ synchronization, phase $\phi_1$ within $m$ cycles of oscillator 1 that grows from 0 to $2\pi m$ presents the same value at time $t_{k_2}$ and $t_{k_2+n}$, i.e., $\psi_m(t_{k_2}) = \psi_m(t_{k_2+n})$. According to this concept, we first transform $\psi_m(t_{k_2})$ to $\Psi_{n,m}(t_{k_2})$ using equation (2.5). Then the degree $\gamma_{n,m}$ of $n$ : $m$ synchronization can be evaluated by equation (2.6) [10].

$$\Psi_{n,m}(t_{k_2}) = \frac{2\pi}{m}\left\{[\psi_m(t_{k_2})\cdot n] \bmod m\right\} \tag{2.5}$$

$$\gamma_{n,m} = [\frac{1}{N}\sum_{k_2}\cos(\Psi_{n,m}(t_{k_2}))]^2 + [\frac{1}{N}\sum_{k_2}\sin(\Psi_{n,m}(t_{k_2}))]^2 \tag{2.6}$$

where $N$ represents the number of marker events of oscillator 2 in a given window length. The value of $\gamma_{n,m}$ ranges from 0 to 1, where $\gamma_{n,m} = 1$ indicates the case of complete synchronization, and $\gamma_{n,m} = 0$ reveals the fact of complete desynchronization.

### 2.2 Time-phase Bispectral Analysis

Bispectral analysis is also a tool to observe the property of nonlinear (quadratic) phase coupling between oscillators [11]. A number of methods for estimating the bispectrum $\hat{B}(k,l)$ have been well known. We skip the description.

## 3. EXPERIMENT AND SIGNAL ANALYSIS

### 3.1 Experimental Setup and Procedure

This study involved two groups of subjects, the experimental group including subjects with Chan-meditation experience and the control group including subjects without any meditation experience. Background of subjects in each group is listed in Table 3.1.

Table 3.1 Subjects of experimental and control groups

| | Experimental group | Control group |
|---|---|---|
| Number of subjects | 7 | 9 |
| Sex (male : female) | 5 : 2 | 8 : 1 |
| Age (years) | 26.4 ± 2.5 | 25.3 ± 3.3 |
| Meditation experience (years) | 5.9 ± 2.6 | |

The experimental procedure of this study is illustrated in Fig. 3.1. Because the human cardiac function can be regulated by autonomic nervous system (ANS), the experiments were conducted during the same period (3:00pm to 5:00pm) to ensure the approximately same state of ANS of all subjects. The experiments comprised two sessions. During Session 1, subjects of both groups rested, in a ~70° head-up back-tilt position with eyes closed, for 10 minutes. During Session 2, subjects of control group continued resting for 20 minutes; on the other hand, experimental subjects began meditation for 20 minutes. Experimental subjects, following their routine meditation habit, meditated with either full-lotus or half-lotus posture, with eyes closed.

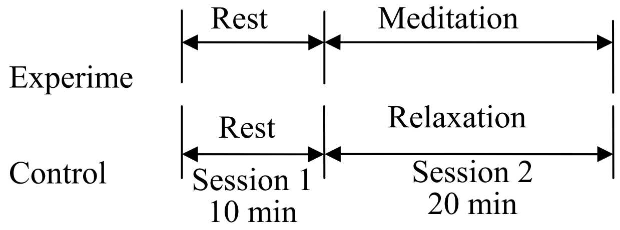



Fig. 3.1 Experimental procedure.

ECG and respiratory signals were measured using PowerLab biosignal recording system (ADInstruments, Sydney, Australia) and then displayed and saved on a personal computer using the software Chart4 (ADInstruments, Bella Vista, Australia).

### 3.1.1 Measurement of ECG signal

The ECG signal was recorded using Lead Ⅰ of standard bipolar limb leads [12]. 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) were applied in this study. The ECG was pre-filtered by a 0.3-200 Hz bandpass filter and digitized by a sampling rate of 1000 Hz.

### 3.1.2 Measurement of Respiratory signal

Respiratory signal was recorded using a piezo-electric transducer (Model 1132 Pneumotrace II (R), UFI, Morro Bay, CA, USA), that was wrapped around the belly passing the navel. The respiratory signal was pre-filtered by a lowpass filter with cutoff frequency of 5 Hz and digitized at the sampling rate of 1000 Hz.

## 3.2 Strategies for Synchronization Analysis

### Step 1. Pre-processing

Power spectrums of QRS complexes and respiratory signals are approximately 10-30 Hz and 0.2-0.3 Hz [13,14]. Accordingly, in pre-processing stage, we applied Matlab’s built-in polyphase filter implementation, including anti-aliasing (lowpass) FIR filter, to down-sample the raw ECG and respiratory signals, respectively, to the rate of 200 samples and 20 samples per second.

**Step 2. Formulate Synchrogram**

To construct the cardiorespiratory synchrogram, we sketched the normalized relative phase $\psi_m(t_{k_2})$ of respiratory signal at time $t_{k_2}$ identified as the appearances of R peaks of ECG. In this research, we observed the cardiorespiratory synchronization within 3 respiratory cycles.

**Step 3. Calculate Frequency Ratio** $f_h/f_r$

The instantaneous frequency of heart beating $f_h$ was calculated by inversing the time interval between two adjacent R peaks of ECG signal, while that of the respiration $f_r$ was the reciprocal of the time interval between two respiratory peaks.

**Step 4. Quantify the Synchronization Degree**

To evaluate the synchronization degree, the following procedure was proposed:

(1) The maximum and minimum values of frequency ratio, $min[f_h/f_r]$ and $max[f_h/f_r]$, were derived.

(2) We determined all possible pairs of $(n,m)$'s such that $n/m$ satisfied: $min[f_h/f_r] \leq n/m \leq max[f_h/f_r]$. Note that all pairs $(n/m)$'s, after being reduced, were considered to be the same if they resulted in the same ratio.

(3) Following equations (2.5)-(2.6) , synchronization degree, $\gamma_{n,m}(t_{k_2})$, of qualified $(n,m)$ pairs could be calculated with a window centered at time $t_{k_2}$. In this study, we employed the window length of 60 consecutive R peaks, with the moving step size of one R peak.

(4) The synchronization degree at a given time $t_{k_2}=T_{sd}$ was determined by finding the maximum value along the vertical line defined by $\gamma_{n,m}(t_{k_2}=T_{sd})$.

**Step 5. Quantify the Synchronization Duration**

To systematically determine the value of threshold $\alpha$, the following procedure was proposed:

(1) The values of $\gamma_{\max}(t_{k_2})$ were averaged every minute and the mean values were denoted as $\gamma_{\text{mean}}(t)$.

(2) We found that the largest value of the histogram occurred at $\gamma_{\text{mean}}(t)$ =0.2. Therefore, the threshold was determined to be $\alpha = 0.2$.

### 3.3 Strategies for Time-phase Bispectral Analysis

**Step 1. Pre-processing**

Fundamental frequencies of ECG and respiratory signals are approximately 1.2 Hz and 0.3 Hz [13]. Accordingly, raw ECG and respiratory signals originally recorded with sampling rate of 1000 Hz were downsampled to 10 Hz using Matlab's built-in polyphase filter implementation, including anti-aliasing, lowpass FIR filter with cutoff frequency 5 Hz. Then Chebyshev I IIR highpass filter with cutoff frequency 0.04 Hz was used to remove the baseline drift.

**Step 2. Estimate Cross-Bispectrum**

By equation (2.12), the cross-bispectrum $\hat{B}_{xyx}(k,l,\ m)$ was estimated. Here, $k$ represents the frequency of ECG signal, $l$ represents the frequency of respiratory signal, and $m$ represents the time. The length of time window was selected to be 10 times of the period of slower signal, i.e. respiratory signal, to get reliable FFT (fast Fourier Transform) result. The slowest frequency of respiratory signals in our study was about 0.2 Hz (period: 5 sec per breath). We thus selected the window length to be 1 minute. To observe the time-varying behavior in more details, the moving step was selected to be 1 second.

**Step 3. Calculate Biamplitude and Biphase at Bifrequency ($f_e, f_r$)**

Biamplitude and biphase were evaluated at bifrequency ($f_e, f_r$) for each window frame. The bifrequency ($f_e$, $f_r$) of each window was determined by the maximum-power frequencies of ECG and respiratory signals respectively.

**Step 4. Quantify the Coupling Degree**

The coupling degree is determined by

$$\lambda(m) = A_{normalized}\ (m) \times \gamma_{\phi}(m) \tag{3.1}$$

where $A_{normalized}(m)$ is the normalized biamplitude for a given window, that is derived by first dividing the biamplitude by total power of cross-bispectrum in $0 \le f_e, f_r \le f_s/2$ and then normalizing the results of all subjects to the range [0 1]. The $\gamma_{\phi}(m)$, denoting the constant degree of biphase, can be calculated by equation (2.15) for a given window centered at time $m$.

**Step 5. Quantify the Coupling Length**

To quantify the coupling length, a threshold $\alpha$ needs to be determined first. To determine an appropriate value of $\alpha$, the following procedure was proposed:

(1) A new sequence $\lambda_{\text{mean}}(t)$ containing the results of moving average of $\lambda(m)$ was

obtained using a window size of one minute without overlap.

(2) Maximum of the histogram indicates the majority of phase-coupling distribution. Accordingly, we selected $\alpha = 0.2$ for this specific case.

# 4. RESULTS

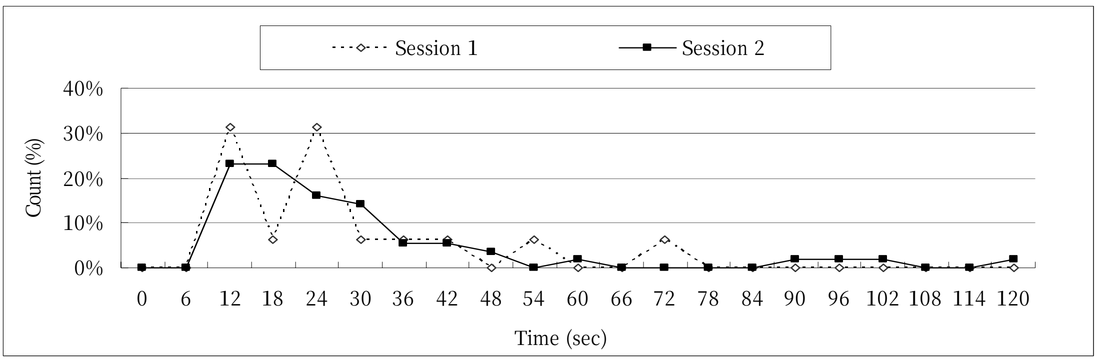
## 4.1 **Results of Synchronization Analysis**

To investigate the effects of meditation on cardiorespiratory synchronization, we compared three parameters, that is, lasting length, number of epochs, and total length, between the experimental and control group. The paired *t* test was applied to examine the significant difference of parameters between Session 1 and Session 2. The results are summarized in Table 4.1 and further explained in the following sub-sections.

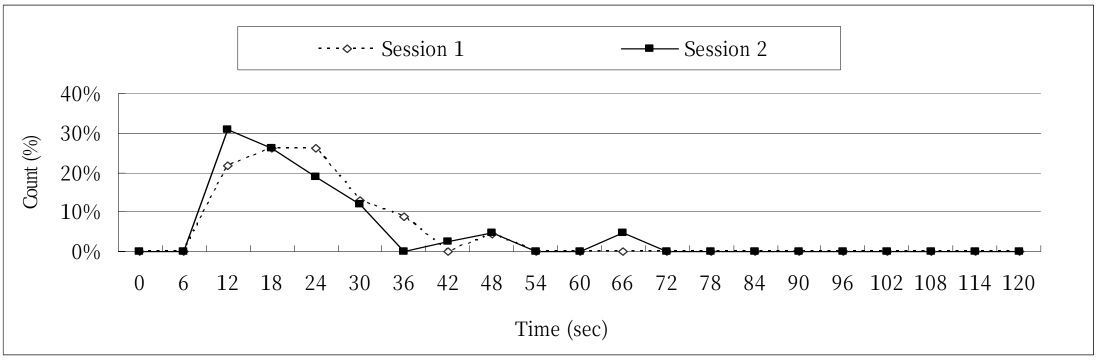
Table 4.1 Mean values of three synchronization parameters analyzed for the experimental and control group.

| | Experimental Group (n=7) | | Control Group (n=9) | | *p*-Value for comparison of | |
|---|---|---|---|---|---|---|
| | S1 | S2 | S1 | S2 | Exp. Group S1 vs. S2 | Con. Group S1 vs. S2 |
| Lasting length (seconds/epoch) | 27.9±19.6 | 21.4±15.3 | 17.3±7.6 | 24.9±15.7 | 0.226 | 0.161 |
| Number of epochs (counts/10 minutes) | 2.3±1.5 | 4.0±2.4 | 2.6±1.5 | 2.3±1.9 | 0.023* | 0.355 |
| Total length (seconds/10 minutes) | 55.6±34.9 | 107.0±92.4 | 51.8±35.0 | 47.5±34.2 | 0.034* | 0.360 |

S1= Session 1; S2=Session 2; Exp.=Experimental group; Con.=Control group; *Significantly different ($p<0.05$).




(a)




(b)

Fig. 4.1 Histograms of lasting length of synchronization for
(a) experimental group, and (b) control group.

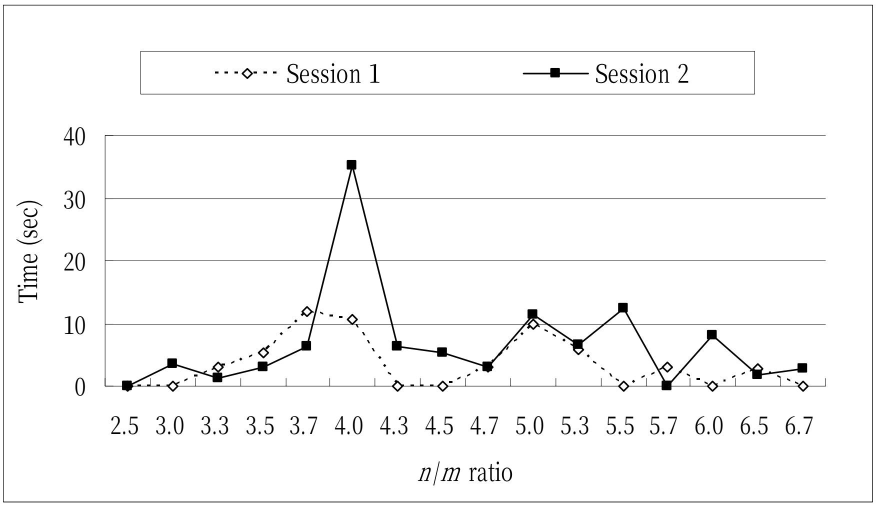
### 4.1.1 Comparison of Lasting Length

The definition of "lasting length" here is the duration of an epoch with synchronization degree higher than threshold. By statistical analysis for the mean values of lasting length of synchronization, both groups revealed no significant difference between two sessions, as shown in Table 4.1 and Fig. 4.1. This indicates that, in general, neither meditation nor rest could noticeably affect the lasting length of synchronization.

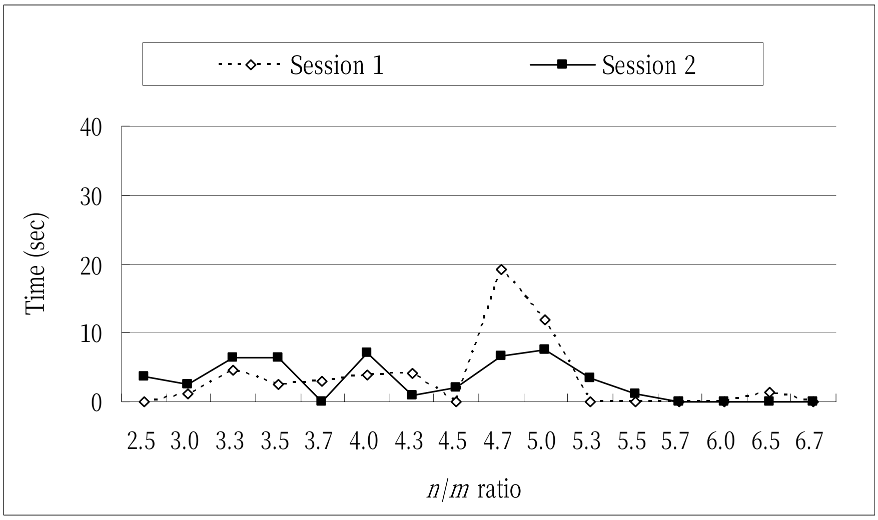
### 4.1.2 Comparison of Number of Epochs

The definition of "number of epochs" here is the amount of epochs with synchronization degree higher than threshold in a ten minutes time duration. As shown in Table 4.1, mean values of the number of synchronization epochs revealed insignificant difference between main session and pre-session in control group. As regards the experimental group, it increased considerably during meditation, in comparison with the mean number observed in the pre-session background recording.

Further, we investigated the synchronization length for various ($n/m$) ratios. Fig. 4.2 displays the average length of synchronization (in seconds) versus ($n/m$) ratio. According to Fig. 4.2 (a), significant increase in the length of synchronization was observed in experimental group at the ratio ($n/m$) = 4 (i.e., 4:1 synchronization) in the main-session recording, from which we may infer that one respiration accompanied four heart beats during the Chan-meditation course. On the other hand, the control group only revealed a slight increase at the ratio ($n/m$)=4.7 (i.e., 14:3 synchronization) in the (pre-session) background recording, without any particular event in the main-session recording (refer to Fig. 4.2 (b)).




(a)




(b)

Fig. 4.2 Average length of synchronization for different (*n*/*m*) ratios in (a) experimental group and (b) control group.

### 4.1.3 Comparison of Total Length

The definition of "total length" here is the sum of lengths of all epochs with synchronization degree higher than threshold in a 10 minutes time period. As shown in Table 4.1, mean values of the total length of synchronization indeed did not change from pre-session to main-session recording in control group. However, experimental group exhibited an almost twice increase in the total length of synchronization during meditation while compared with the background recording in Session 1.

## 4.2 **Results of Time-phase Bispectral Analysis**

To investigate the effects of meditation on cardiorespiratory coupling, we compared three parameters, that is, lasting length, number of epochs, and total length, are compared between experimental group and control group. The paired *t* test was applied to examine the significant difference of parameters between Session 1 and Session 2. The results are summarized in Table 4.2 and further explained in the following sub-sections.

Table 4.2 Mean values of three nonlinear coupling parameters analyzed for the experimental and control group.

| | Experimental Group (n=7) | | Control Group (n=9) | | *p*-Value for comparison of | |
|---|---|---|---|---|---|---|
| | S1 | S2 | S1 | S2 | Exp. Group S1 vs. S2 | Con. Group S1 vs. S2 |
| Lasting length (seconds/epoch) | 30.6±12.7 | 32.8±16.6 | 20.1±13.4 | 24.5±12.9 | 0.399 | 0.221 |
| Number of Epochs (counts/10 minutes) | 4.1±2.3 | 6.1±2.5 | 3.6±3.3 | 4.0±2.7 | 0.038* | 0.360 |
| Total length (seconds/10 minutes) | 127.9±83.6 | 201.1±120.6 | 85.8±76.3 | 117.3±98.7 | 0.131 | 0.236 |

S1= Session 1; S2=Session 2; Exp.=Experimental group; Con.=Control group; *Significantly different ($p<0.05$).

### 4.2.1 **Comparison of Lasting Length**

By statistical analysis for the mean values of lasting length of nonlinear coupling, both groups revealed no significant difference between two sessions in both groups, as shown in Table 4.2. This indicates that, in general, neither meditation nor rest could noticeably affect the lasting length of nonlinear coupling.

### 4.2.2 **Comparison of Number of Epochs**

As shown in Table 4.2, the mean values of the number of nonlinear coupling epochs revealed insignificant difference between main session and pre-session in control group. As regards the experimental group, it increased considerably during meditation, in comparison with the mean number observed in the pre-session background recording.

### 4.2.3 **Comparison of Total Length**

As shown in Table 4.2, the mean values of the total length of nonlinear coupling revealed insignificant difference between main session and pre-session in both groups.

## 4.3 **Correlation between Phase Synchronization and Nonlinear Coupling**

To examine this hypothesis that the nonlinear coupling nature of cardiorespiratory system determined by time-phase cross-bispectral analysis could be correlated with cardiorespiratory phase synchronization in a sense, we conducted a quantitative analysis by calculating the correlation coefficients between them. We first interpolated the sequences (with 1 second resolution) for the instantaneous degree of both the phase synchronization and the nonlinear coupling. Next, the correlation coefficients were calculated for these two new sequences using two-minute window size with one-minute overlap. We roughly classified the correlation into three states: positive correlation ($\gamma$ ($d$)≥0.3), negative correlation ($\gamma$ ($d$) ≤-0.3), and little correlation (-0.3 <$\gamma$($d$) <0.3).

Table 4.3 lists, for each group in a given session, the percentage of total time interval of each correlation state. To examine the statistical significance of percentage difference between Session 1 and Session 2, the paired *t* test was applied and the significant levels were selected to be $p$<0.05. Apparently, only the percentage of positive correlation increases significantly in experimental group from Session 1 to Session 2.

Table 4.3 Percentage of total time interval of each correlation state.

| Correlation states | Experimental Group (n=7) | | Control Group (n=9) | | *p*-Value for comparison of | |
|---|---|---|---|---|---|---|
| | S1 | S2 | S1 | S2 | Exp. Group S1 vs. S2 | Con. Group S1 vs. S2 |
| Positive correlation ($\gamma$($d$)≥0.3) | 28.6% | 43.7% | 22.2% | 23.5% | 0.011* | 0.451 |
| Negative correlation ($\gamma$($d$) ≤-0.3) | 14.3% | 8.4% | 23.8% | 11.8% | 0.211 | 0.111 |
| No significant correlation (-0.3<$\gamma$($d$)<0.3) | 57.1% | 47.9% | 54.0% | 64.7% | 0.154 | 0.094 |

S1= Session 1; S2=Session 2; Exp.=Experimental group; Con.=Control group; *Significantly different (p<0.05).

# 5. CONCLUSION AND DISCUSSION

## 5.1 **Conclusion and Discussion**

In regard to the study on synchronization phenomenon, Number of the synchronous epochs and the total synchronization length increased significantly ($p$=0.023 and $p$=0.034, respectively) during meditation as compared with the results for subjects at rest. We therefore might infer from the results that meditation produces different effects on cardiorespiratory synchronization other than normal rest does.

In the aspect of investigating the nature of nonlinear coupling, Number of the coupling epochs increased significantly ($p$ = 0.038) during meditation as compared with that studied on subjects at rest.

In regard to the coincidence between phase synchronization and nonlinear coupling of cardiorespiratory system, we found that the percentage of positive correlation increased significantly ($p$ = 0.011) during meditation. It suggests that under nonlinear coupling, meditation might enhance the phase synchronization between cardiac and respiratory systems.

### 5.2 Future Work

In this study, we only investigated the coupling nature of characteristic frequencies of ECG and respiratory signals. The coupling caused by interaction of some other frequency components may play an important role in studying the physiological model under meditation. Besides, it has been reported in the literatures that cardiorespiratory synchronization might be related to the central neural regulation [4] and brain activity [5]. Hence, for profound understanding of the Chan-meditation process and effects, EEG signals should be included to explore the mutual interaction between the brain and cardiorespiratory system.

## Reference

[1] Berntson G.G., Cacioppo J.T., Quigley K.S., "Respiratory sinus arrhythmia: autonomic origins, physiological mechanisms, and psychophysiological implications," *Psychophysiology*, vol.30(2), pp.183－196, March 1993.

[2] Schäfer C., Rosenblum M. G., Kurths J., Abel H.-H., "Heartbeat synchronised with respiration," *Nature*, vol.392(6673), pp.239－241, Mar. 1998.

[3] Jamšek J., Stefanovska A., McClintock P. V. E., "Nonlinear cardio-respiratory interactions revealed by time-phase bispectral analysis," *Phys. Med. Biol.*, vol.49(18), pp:4407－4425, Sep. 2004.

[4] Schäfer C., Rosenblum M. G., Abel H.-H., Kurths J., "Synchronization in the human cardiorespiratory system," *Phys. Rev. E*, vol.60(1), pp.857－870, July 1999.

[5] Bartsch R., Kantelhardt J. W., Penzel T., Havlin S., "Experimental evidence for phase synchronization transitions in the human cardiorespiratory system," *Phys. Rev. Lett*, vol.98(5), Feb. 2007.

[6] Rosenblum M. G., Pikovsky A. S., Kurths J., "Phase synchronization of chaotic oscillators," *Phys. Rev. Lett.*, vol.76(11), pp.1804－1807, March 1996.

[7] Jamšek J., Stefanovska A., McClintock P. V. E., Khovanov I. A., "Time-phase bispectral analysis," *Phys. Rev. E*, vol.68(1), July 2003.

[8] Stratonovich R.L., *Topics in the Theory of Random Noise.* New York: Gordon and Breach, 1963.

[9] Pikovsky A., Rosenblum M., Kurths J., "Phase synchronization in regular and chaotic systems," *International Journal of Bifurcation and Chaos*, vol.10(10), pp. 2291－2305, 2000.

[10] Rosenblum M.G., Pikovsky A.S., Kurths J., Schäfer C., Tass P.A., "Phase synchronization: from theory to data analysis," *in Neuro-informatics and Neural Modeling, volume 4 of Handbook of Biological Physics.* eds. Moss F. and Gielen S., Amsterdam: Elsevier Science, 2001.

[11] Nikias C.L., Petropulu A.P., *Higher-Order Spectra Analysis: A Nonlinear Signal Processing Framework.* Englewood Cliffs, N.J.: Prentice-Hall, 1993.

[12] Goldshlager N., Goldman M.J., *臨床心電圖學.* 廖述朗, 初版, 臺北市: 藝軒圖書出版社, 1995.

[13] Stefanovska A., Bracic M., "Physics of the human cardiovascular system," *Contemp. Phys.*, vol.40(1), pp.31－55, 1999.

[14] Köhler B.U., Hennig C., Orglmeister R., "The principles of software QRS detection," *IEEE engineering in medicine and biology magazine*, vol.21(1), pp.42－57, January 2002.

# Appendix A

## Formal Chan-meditation Practice

Formal Chan-meditation course normally begins with a brief, solemn ritual called 開經偈 signifying “the opening ceremony of the practice towards complete enlightenment.” In the next 5-10 minutes, the class supervisor (normally, the experienced practitioner) shares wisdom words preached by the enlightened Chan Master, Wu Chueh Miao Tien, the 85th patriarch of orthodox Dharma-Chan sect. Meanwhile, practitioners sit calmly with meditation posture and belly breathing, yet, eyes opening.

Then, formal Chan-meditation session begins. In the beginning meditation, practitioners focus on particular chakras to activate the intrinsic potency and wisdom of those chakras. Gradually, the entire body-mind-spirit enters into a field of harmony after transcending the physical, mental, emotional and conscious realm. The goal of Chan meditation is to realize the *True Self* with eternal wisdom.

After the meditation session, practitioners open eyes and listen to the sharing from the supervisor for about ten more minutes. Then, the class ends with a brief closing ritual and the chanting of *The Song of True Self.*

附件二

# 國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

| |
|---|
| 1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估<br>■ 達成目標<br>□ 未達成目標（請說明，以 100 字為限）<br>□ 實驗失敗<br>□ 因故實驗中斷<br>□ 其他原因<br>說明： |
| 2. 研究成果在學術期刊發表或申請專利等情形：<br>論文：■已發表 □未發表之文稿 □撰寫中 □無<br>專利：□已獲得 □申請中 □無<br>技轉：□已技轉 □洽談中 □無<br>其他：（以 100 字為限） |
| 3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）（以 500 字為限）<br><br>本研究成果發表於 International Journal of Cardiology (IF: 3.469)，對於心血管醫學界具有相當影響。以心肺相位同步作為分析指標，證實禪坐方式可以有效提升心肺交互作用、達到紓解壓力之效果，並得以強健心肺功能。 |

附件五

# 國科會補助專題研究計畫項下赴國外(或大陸地區)出差或研習心得報告

日期： 99 年 9 月 6 日

| | | | |
|---|---|---|---|
| 計畫編號 | NSC 98－2221－E－009－100－ | | |
| 計畫名稱 | 禪坐之心肺交互作用與解壓研究 | | |
| 出國人員姓名 | 羅佩禎 | 服務機構及職稱 | 國立交通大學 電機工程學系<br>教授 |
| 出國時間 | 99 年 7 月 11 日<br>至<br>99 年 7 月 19 日 | 出國地點 | 大陸北京、上海 |

## 一、 國外(大陸)研究過程

The principal investigator (Lo, Pei-Chen) has been developing close research collaboration with the School of Computer & Information Technology in BJTU (Beijing Jiaotong University) since 2007. In 2008, Dr Q. Zhu (諸強), associate professor in the Department of Biomedical Engineering (生物醫學工程系) visited my laboratory to cooperate in the project “Microstate Analysis of Alpha-Event Brain Topography during Chan Meditation.” She mainly worked on the wavelet analysis of multi-channel EEG (electroencephalograph) signals. I supervised my graduate students on the task of *microstate analysis*. The collaboration brought forth a paper reported in ICMLC (International Conference on Machine Learning and Cybernetics) 2009 conference. Afterwards, the School and Department invited me to visit them and give a presentation of my research on biomedical signal analysis (Fig. 1).

In Beijing, I also paid a visit to BIT (Beijing Institute of Technology). I was invited by Professor Qinglin Wang who, with research major in control engineering, is currently the director of International Office of BJT. Professor Yao Lu (陸耀，

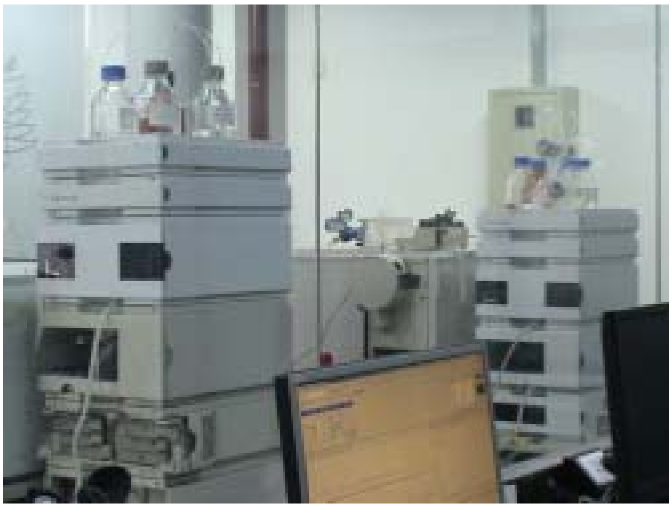
Department of Computer Science and Technology) and Professor 唐曉英 in the Department of Life Science introduced their research facilities and environment to me (Fig. 2).

| | |
|---|---|
|  |  |
| Chairman 劉杰教授 of the department (left first) and faculties (right two) and me (left second). | Laboratory of Biomedical signal analysis |

← Biomedical signal analysis interface card

Fig. 1 Visit to the Department of Biomedical Engineering in BJTU and give a talk.

陸耀(left) and 唐曉英(right)



HPLC 液相層析儀 for protein separation in Department of Life Science

Fig. 2 Visit to the Department of Life Science in BIT.

When attending the ICMLC 2009 conference to present the paper "Microstate Analysis of Alpha-Event Brain Topography during Chan Meditation," I met Dr. Qingsheng Ren (任慶生), associate professor in the Department of Computer Science & Engineering, SJTU (Shanghai Jiao Tong University), who listened to my talk in the L. Zadeh Best Paper Award Competition. Professor Ren then invited me to give a talk in his department.

My talk was scheduled for July 15, 2010 and the topic of my talk was: Body-Mind-Spirit Biomedical Engineering Research. Outline of my talk included:

- Scientific Evidences on Meditation Effects and Benefits
- Medical Studies, Clinical Therapeutic Aids, Daily-life Applications
- Researches and Findings in my Lab since 1998
- Hypothesis— Life model and Chan mechanisms

Regarding the *Researches and Findings in my Lab since 1998*, I first presented a diagram (Fig. 3) illustrating the protocol of my research. Fig. 4 shows some results of Chan-meditation study presented in my talk in SJTU.

In my talk, Professors Lu and Ren and their graduate students asked several questions about EEG research since they just launched the study in the relevant area. Both Professors Lu and Ren were very interested in my research on Chan meditation and look forwards to our future research collaboration.

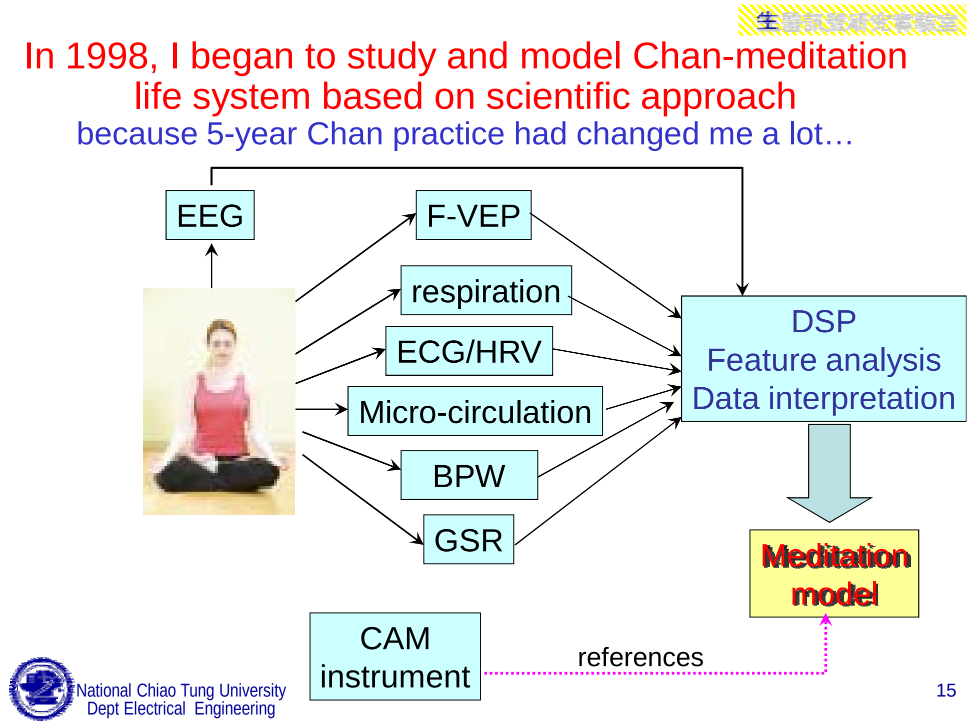



Fig. 3 Protocol of my researches since 1998.

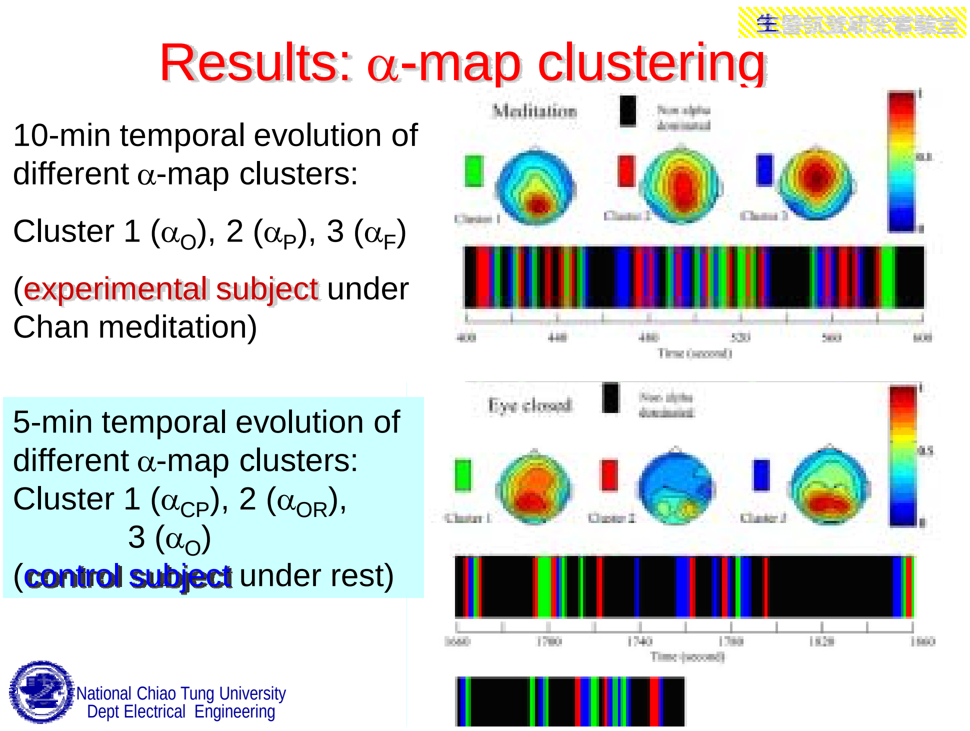
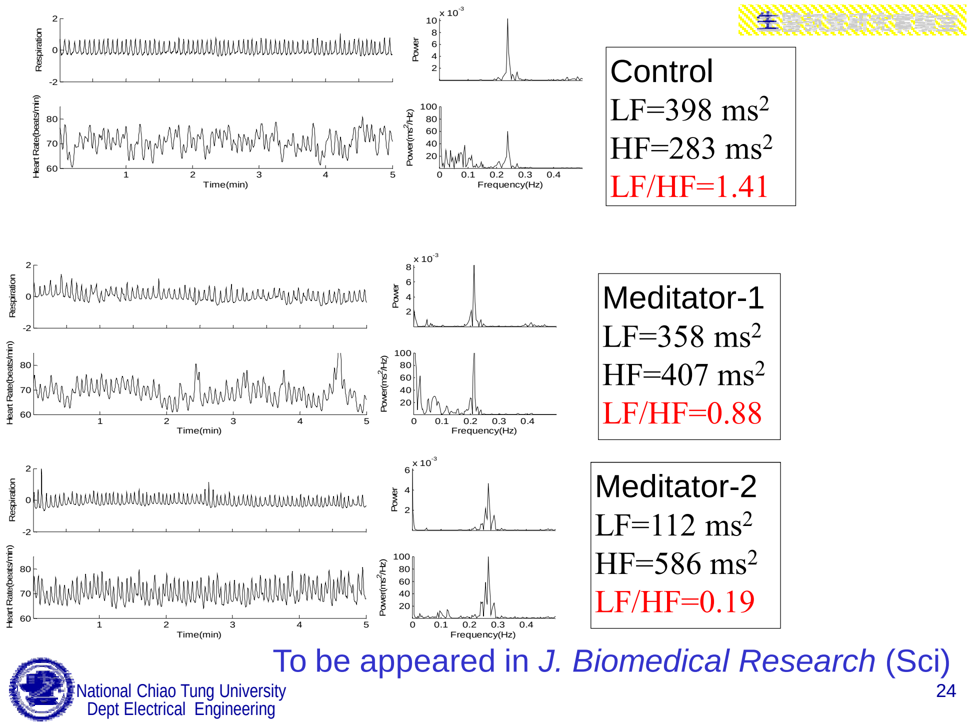



Fig. 4 Partial results of my researches in Chan-meditation life model.



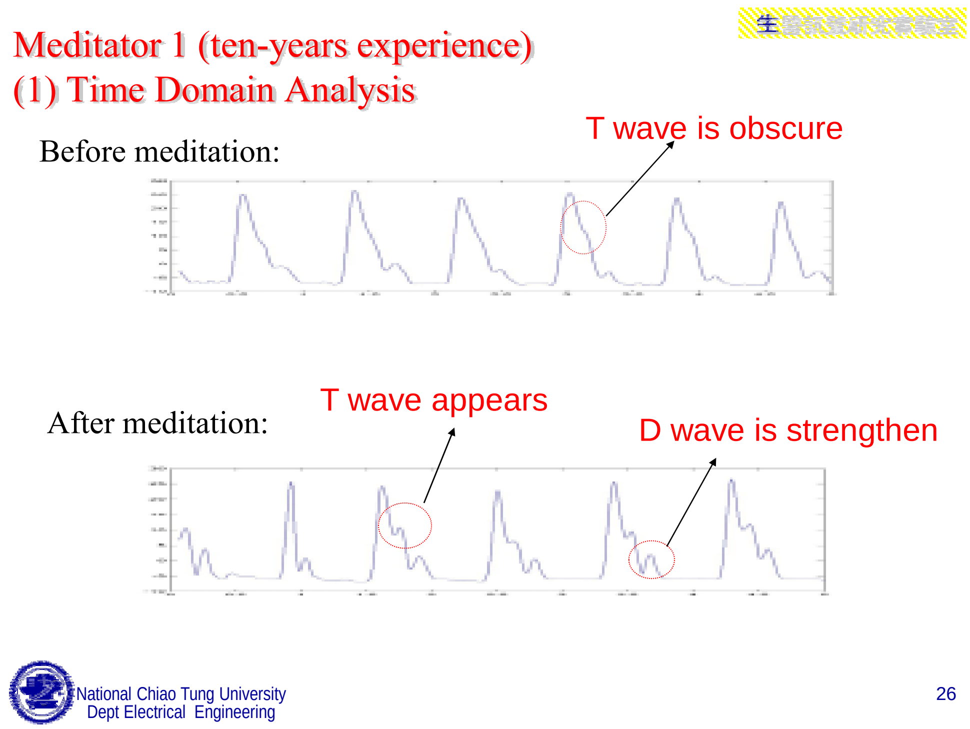




Fig. 4 (continue).

附件五

# 國科會補助專題研究計畫項下赴國外(或大陸地區)出差或研習心得報告

日期：99 年 9 月 6 日

| | | | |
|---|---|---|---|
| 計畫編號 | NSC 98－2221－E－009－100－ | | |
| 計畫名稱 | 禪坐之心肺交互作用與解壓研究 | | |
| 出國人員姓名 | 羅佩禎 | 服務機構及職稱 | 國立交通大學 電機工程學系<br>教授 |
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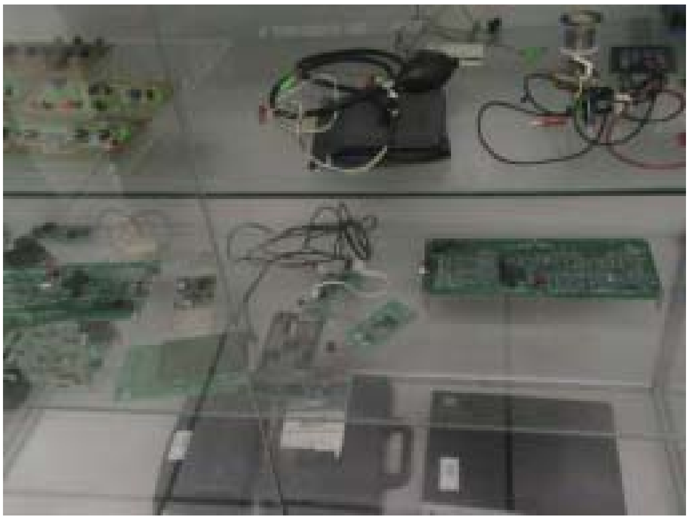
Laboratory of Biomedical signal analysis



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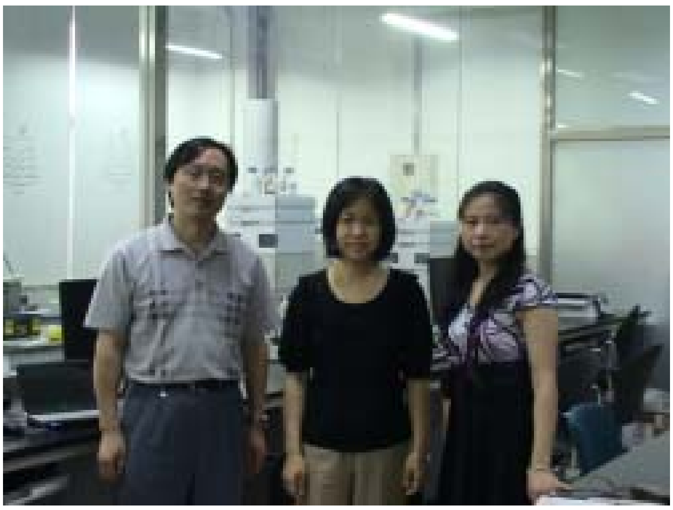

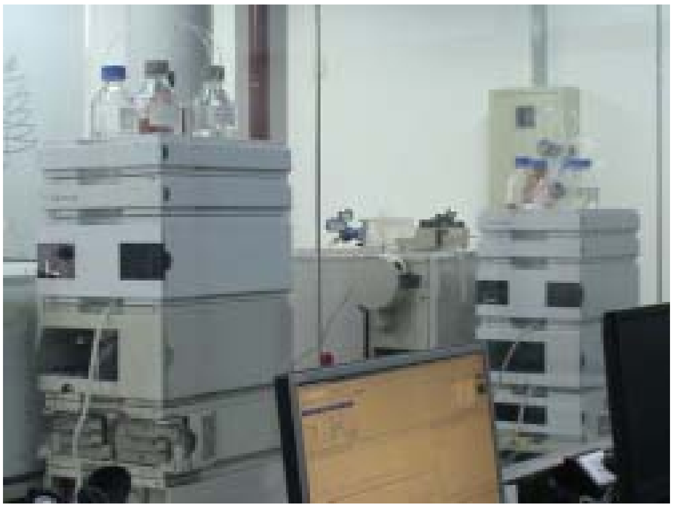


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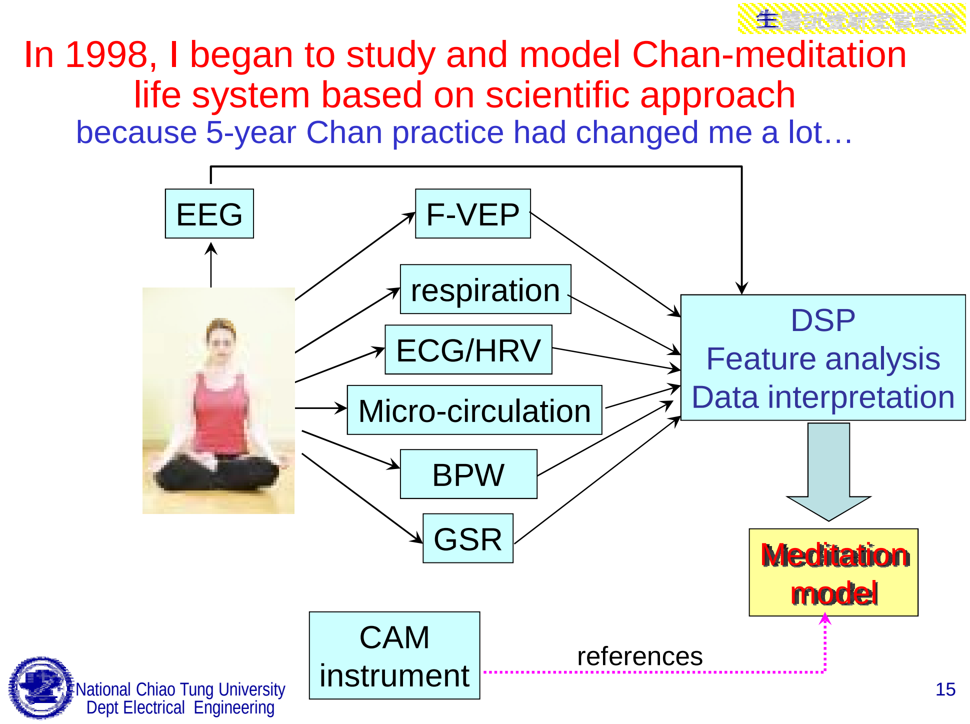


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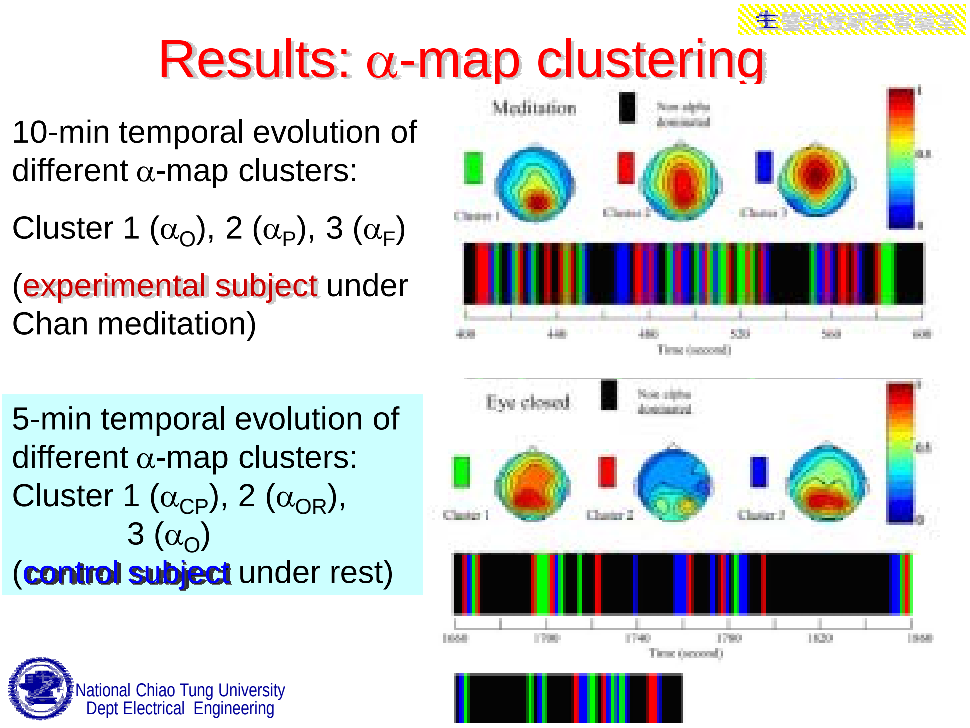


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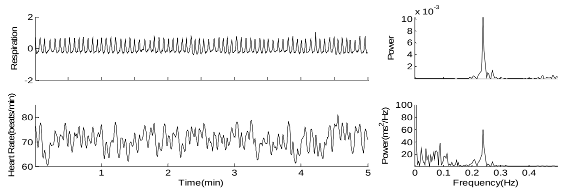
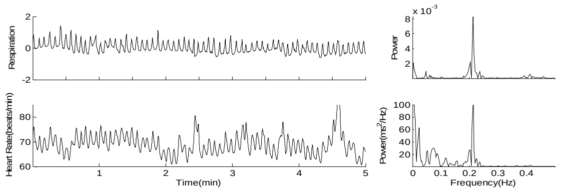
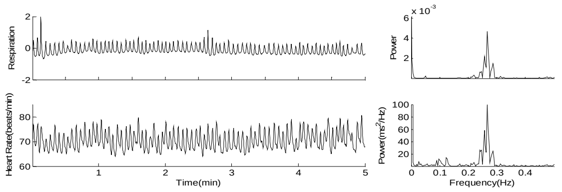



Control
LF=398 $ms^2$
HF=283 $ms^2$
LF/HF=1.41




Meditator-1
LF=358 $ms^2$
HF=407 $ms^2$
LF/HF=0.88




Meditator-2
LF=112 $ms^2$
HF=586 $ms^2$
LF/HF=0.19

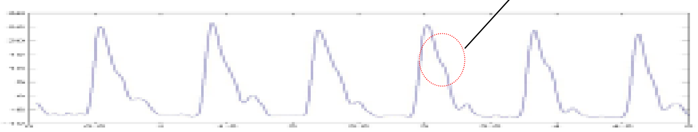
To be appeared in *J. Biomedical Research* (Sci)



## Meditator 1 (ten-years experience)
## (1) Time Domain Analysis

Before meditation:

T wave is obscure



After meditation:

T wave appears

D wave is strengthen

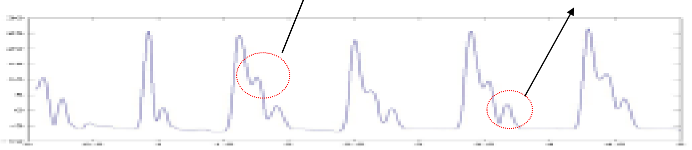




Fig. 4 (continue).

無研發成果推廣資料

# 98 年度專題研究計畫研究成果彙整表

| 計畫主持人：羅佩禎 | | | 計畫編號：98-2221-E-009-100- | | | | |
|---|---|---|---|---|---|---|---|
| 計畫名稱：禪坐之心肺交互作用與解壓研究 | | | | | | | |
| 成果項目 | | | 量化 | | | 單位 | 備註（質化說明：如數個計畫共同成果、成果列為該期刊之封面故事...等） |
| | | | 實際已達成數（被接受或已發表） | 預期總達成數(含實際已達成數) | 本計畫實際貢獻百分比 | | |
| 國內 | 論文著作 | 期刊論文 | 0 | 0 | 100% | 篇 | |
| | | 研究報告/技術報告 | 0 | 0 | 100% | | |
| | | 研討會論文 | 2 | 0 | 100% | | |
| | | 專書 | 3 | 0 | 100% | | |
| | 專利 | 申請中件數 | 0 | 0 | 100% | 件 | |
| | | 已獲得件數 | 0 | 0 | 100% | | |
| | 技術移轉 | 件數 | 0 | 0 | 100% | 件 | |
| | | 權利金 | 0 | 0 | 100% | 千元 | |
| | 參與計畫人力（本國籍） | 碩士生 | 8 | 0 | 100% | 人次 | |
| | | 博士生 | 1 | 0 | 100% | | |
| | | 博士後研究員 | 0 | 0 | 100% | | |
| | | 專任助理 | 0 | 0 | 100% | | |
| 國外 | 論文著作 | 期刊論文 | 1 | 0 | 100% | 篇 | |
| | | 研究報告/技術報告 | 0 | 0 | 100% | | |
| | | 研討會論文 | 0 | 0 | 100% | | |
| | | 專書 | 0 | 0 | 100% | 章/本 | |
| | 專利 | 申請中件數 | 0 | 0 | 100% | 件 | |
| | | 已獲得件數 | 0 | 0 | 100% | | |
| | 技術移轉 | 件數 | 0 | 0 | 100% | 件 | |
| | | 權利金 | 0 | 0 | 100% | 千元 | |
| | 參與計畫人力（外國籍） | 碩士生 | 1 | 0 | 100% | 人次 | |
| | | 博士生 | 1 | 0 | 100% | | |
| | | 博士後研究員 | 0 | 0 | 100% | | |
| | | 專任助理 | 0 | 0 | 100% | | |

| | |
|---|---|
| 其他成果<br>(無法以量化表達之成果如辦理學術活動、獲得獎項、重要國際合作、研究成果國際影響力及其他協助產業技術發展之具體效益事項等，請以文字敘述填列。) | 獲得重要的禪坐心肺交互作用結果，得到多位國際學者的重視、並索取發表論文電子檔。 |

| | 成果項目 | 量化 | 名稱或內容性質簡述 |
|---|---|---|---|
| 科教處計畫加填項目 | 測驗工具(含質性與量性) | 0 | |
| | 課程/模組 | 0 | |
| | 電腦及網路系統或工具 | 0 | |
| | 教材 | 0 | |
| | 舉辦之活動/競賽 | 0 | |
| | 研討會/工作坊 | 0 | |
| | 電子報、網站 | 0 | |
| | 計畫成果推廣之參與（閱聽）人數 | 0 | |

# 國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

| |
|---|
| 1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估<br>■達成目標<br>□未達成目標（請說明，以 100 字為限）<br>□實驗失敗<br>□因故實驗中斷<br>□其他原因<br>說明： |
| 2. 研究成果在學術期刊發表或申請專利等情形：<br>論文：■已發表 □未發表之文稿 □撰寫中 □無<br>專利：□已獲得 □申請中 ■無<br>技轉：□已技轉 □洽談中 ■無<br>其他：（以 100 字為限） |
| 3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）（以 500 字為限）<br>本研究成果發表於 International Journal of Cardiology (IF: 3.469)，對於心血管醫學界具有相當影響。以心肺相位同步作為分析指標，證實禪坐方式可以有效提升心肺交互作用、達到紓解壓力之效果，並得以強健心肺功能。 |