行政院國家科學委員會專題研究計畫　成果報告

禪定腦電波之研究(3/3)

計畫類別：個別型計畫
計畫編號：NSC92-2218-E-009-010-
執行期間：92 年 08 月 01 日至 93 年 07 月 31 日
執行單位：國立交通大學電機與控制工程學系

計畫主持人：羅佩禎

報告類型：完整報告
報告附件：出席國際會議研究心得報告及發表論文
處理方式：本計畫涉及專利或其他智慧財產權，1 年後可公開查詢

中　華　民　國 93 年 11 月 9 日

行政院國家科學委員會補助專題研究計畫成果報告

禪定腦電波之研究

A research for the meditation EEG

計畫類別：■個別型計畫　　□整合型計畫
計畫編號：NSC92－2218－E－009－010－
執行期間：90 年 08 月 01 日　至 93 年 07 月 31 日

計畫主持人：羅佩禎
共同主持人：

成果報告類型（依經費核定清單規定繳交）：□精簡報告 ■完整報告

本成果報告包括以下應繳交之附件：
□赴國外出差或研習心得報告一份
□赴大陸地區出差或研習心得報告一份
□出席國際學術會議心得報告及發表之論文各一份
□國際合作研究計畫國外研究報告書一份

處理方式：除產學合作研究計畫、提昇產業技術及人才培育研究計畫、列管計畫及下列情形者外，得立即公開查詢
□涉及專利或其他智慧財產權，■一年□二年後可公開查詢

執行單位：國立交通大學　電機與控制工程學系

中　華　民　國　九十三 年　十一　月　一　日

行政院國家科學委員會專題研究計畫成果報告

禪定腦電波之研究

A research for the meditation EEG

計畫編號： NSC 92-2218-E-009-010
執行期限： 90 年 08 月 01 日至 93 年 7 月 31 日
主持人： 羅佩禎，國立交通大學電機與控制工程學系
共同主持人：
計畫參與人員：

一、中文摘要

隨著「禪定、打坐」不斷被證實其對健康的莫大助益，探究禪定之生理與健康機制更顯得意義重大。在本三年期之研究計畫中，我們的研究焦點在於禪修者的腦電波現象，分別針對禪坐之前、之間、以及下坐之後的腦電波變化，予以深入探究。實驗組為禪宗佛法之修行者（五十位以上），對照組為同年齡層之一般健康人（無禪坐經驗）；同時，為了深入分析腦電波之時間、空間（不同記錄點）、和頻域之特性，我們發展了多元化之腦電波分析方法和技術。分析結果除了呈現多種不同之禪定劇本外，由腦電波所呈現之波形特性，確實反應兩組受測者間之顯著差異，禪定組的腦電波顯然更為「寧靜」。而本研究之更深層的意義則在於——為『禪定系統之生物機制』提出可能之假說。

關鍵詞：禪定、腦電波、禪定腦電波、禪定系統之生物機制。

Abstract

As the Zen meditation has been proved to be of great help to the health, exploration of the physiological signals and health model under Zen meditation becomes more significant. In this three-year research project, we have focused on the EEG (electroencephalographic) phenomena of Zen meditators. We investigated the variations of EEG characteristics before, during, and after Zen meditation. The experimental group consisted of more than fifty Zen-Buddhist practitioners. The control group involved normal, healthy subjects of the same age range (without any experience of meditation). Moreover, we have developed multiphase approaches and techniques to thoroughly explore the temporal, spatial (recording loci), and spectral characteristics of EEG. Results of EEG analysis reveal various meditation scenarios. In addition, the EEG waveform patterns well discriminate the experimental group from control group. Our results evidently demonstrate that Zen-Buddhist practitioners possess the meditation EEG that is much *quieter* than the normal EEG. Significance of this research is the proposal of possible hypotheses to explain the biological mechanism of meditation model.

Keywords: Zen-meditation, electroencephalograph (EEG), meditation EEG, biological mechanism of meditation model.

目錄

I. INTRODUCTION

As the complementary and alternative medicine (CAM) becomes more appealing to the public, researchers begin taking a more serious attitude toward this oriental approach for health maintenance and promotion (Barinaga 2003, Fields et al. 2002**,** Litvak et al. 2001**)**.
Zen-Buddhist practice has become not only the religion but also greatly improved physical and mental health. The background, the biological mechanism, and the intrinsic basis are introduced below.

Discovery of *inner energy* via the orthodox Zen-Buddhism practicing, for more than two-thousand years, reveals a new form of energy other than the physical phenomena (Lo, Huang, Chang, 2003). This form of energy is interpreted by the Zen-Buddhism practitioners as “the radiance of our fundamental nature, the light of wisdom, or the light of eternal life”. In the Zen-Buddhism, the fundamental nature means our "true self", in contrast to the physical entity that is our "phantasmal self" due to its finite duration of existence. The ultimate aim of the orthodox Zen-Buddhism practicing is to attain an eternal state called the *Buddhahood*. The first step toward Buddhahood is to prove the original, true self — discover and uncover the light of eternal life. This light is to be called the *inner energy* or *inner light* in the report.

The *inner energy* differs from the *qi* energy, as stated by the practitioners, the *qi* energy can be ranked into 4 levels: *real qi*, *spiritual qi*, *electrical qi*, and *light qi*. The *qigong* practitioners mostly achieve the *real-qi* level, which belongs to the physical world and, accordingly, is time-varying. The highest level achieved by *qigong* practitioners is the *spiritual qi*. Even reaching this level, one still cannot prove the true self. The *spiritual qi* can be transformed, via orthodox Zen-Buddhism practicing, into *electrical qi* and even *light qi* that is finally the light of eternal life. Although the *inner energy* is an inconceivable, supernatural power, it is not merely a conceptual or hypothetical entity. One can only explore the inner energy by transcending the physiological (the fifth), mental (the sixth), subconscious (the seventh), and Alaya (the eighth) conscious state. The human life system in this state may be interpreted as follows: one shuts off his physical and mental sensors, disables the message transmission passage from the outside world, and is finally freed from the interference from subconsciousness. In the physical world, the human life system lives in the domain of physical, mental, and even subconscious activities. Nevertheless, message originated or conveyed in this domain, to our true self, behaves like the dark cloud covering the brilliance of the sunlight. Speaking in the engineering sense, the signal is contaminated by noise.

The Zen-Buddhism practitioners have discovered that the *inner energy* is the resources of health and bliss. According to our investigation, the practitioners through years of the Zen-Buddhism practicing can change the constitution of their bodies by ignition of the inner energy. A large number of practitioners are found not only to maintain better health (Table 1) but to remain younger and more energetic than the normal people do.

Since two years ago, our research group started investigating the physiological characteristics, mainly focusing on the EEG (electroencephalograph, to be described in details in Section III) signals, of the orthodox Zen-Buddhism practitioners. A number of papers have reported the EEG findings of subjects practicing various meditation techniques (Anand et al. 1961, Banquet 1973, Becker et al. 1981, Bennett et al. 1977, Jevning et al. 1992, King et al. 2002, Wallace 1970, West 1980 Woolfolk 1975). West (1980) summarized those EEG findings and commented on the EEG changes during meditation as follows. On beginning meditation, an increase in alpha amplitude and a decrease in alpha frequency are often observed. Next, the rhythmic theta trains may occur for experienced meditators. Thereafter and very rarely, bursts of high-frequency beta (above 20Hz) are recorded for meditators capable of achieving deep meditation, '*samadhi*' or '*transcendence*'. Thus, it was suggested that the beta-rhythm dominated pattern characterized the EEG of deep meditation stages.

Numerous studies have been focused on physiological and psychological effects of meditation, with few addressed on the underlying mechanisms. The search for physical and psychological correlates of meditation has centered essentially on three methods: Yoga in India, Transcendental Meditation (TM) in the United States, and Zen Buddhism in Japan. Note that the Zen Buddhism in Japan (Kasamatsu 1966) was promulgated from mainland China where the orthodox Zen Buddhism originated. We briefly narrate the promulgating history of Zen Buddhism below.

Buddha Shakyamuni（釋迦牟尼佛） attained the Buddhahood and discovered the eternal truth of the universe in meditation under a linden tree. The eternal truth comprehends the light of the supreme wisdom, the noumenal energy, and the natural powers of the true self. The orthodox Zen Buddhism originated in the affair that Buddha Shakyamuni transmitted this light of wisdom to the Great Kashiyapa（摩訶迦葉尊者） some 2,500 years ago. The same path towards Buddhahood was promulgated to mainland China in 527 by Bodhidharma（達摩祖師）, the 28th patriarch. The current patriarch is Zen master Wu Chueh Miao Tien (or simply "Miao Tien" 悟覺妙天禪師), the 85th patriarch of the orthodox Zen-Buddhism Sect since the Great Kashiyapa. In the promulgating history of orthodox Zen-Buddhism, very few disciples were able to catch the quintessence since it cannot be taught in any form of lectures. Written material and spoken words cannot pass on the true message of Zen. Although there are a few sects imparted from the Zen Buddhism, they cannot be the true Zen without succession to the supreme wisdom and the noumenal energy. The core essence is Zen-Buddhist *practice* rather than Sutra-texts *studying*. The current Zen master Wu Chueh Miao Tien established the Taiwan Zen-Buddhist Association to preach the orthodox Zen-Buddhism. To the best of our knowledge, this is the first systematic and wide-scale study on the meditation EEG of Zen-Buddhist practitioners in Taiwan. It was hoped that this study would provide some basis for further research into the benefits of Zen meditation.

According to the experimental results and practitioners' subjective experience, we report some hypotheses that may account for meditative phenomena during the practice of Zen-Buddhism. Orthodox Zen-Buddhist practitioners, aiming to prove the most original trueself, discover and uncover the *inner* energy or light on the way towards their goal. Perception of the inner light can be comprehended as *resonance*. Uncovering the inner energy optimizes physiological and mental health. In the meditation experiment, a significant correlation was observed between perception of the inner light and electroencephalographic (EEG) alpha blockage. We further examined this phenomenon by recording the EEG from subjects during a *blessing* that the subjects did not know being given. During the blessing period, significant alpha blocking was observed in experimental subjects who had been practicing meditation for years in preparation for being in resonance with the inner light. This report provides a new insight into the debate that meditation benefits our health.

II. MAIN AIM

The study presented here aims to investigate the physiological signals of the Zen-Buddhist practitioners, with the main focus on the multi-channel EEG (electroencephalographical) signals. In fact, our research group has been simultaneously collecting and analyzing the ECG (electrocardiography), GSR (galvanic skin reflex), and VEP (visual evoked potentials) signals during the past three years. In this report, we will present our results in three aspects: (A) alpha-blocking phenomenon in meditation EEG, (B) meditation EEG scenarios, and (C) spatio-temporal characteristics of meditation EEG.

.

III. METHODS

The subjects of this study are divided into two groups: Zen-Buddhist practitioners (experimental subjects) and non-practitioners (control subjects).

EEG background introduction:

In the study we aimed to quantitatively study the brain dynamics (Lo et al. 2000, 2001) in the course of meditation based on the brain electrical activities — EEG signals. The EEG signals, discovered in 1924 by Hans Berger, represent the tracings of summated cortical electrical activity collected by applying multiple recording sensors (called the "EEG electrodes") on the scalp (non-invasive recording) or on the cortex (invasive recording). The cortical potentials actually average the excitatory or inhibitory postsynaptic (EPSP or IPSP) potentials of hundreds of neural cells nearby the recording electrodes. After intensive research for several decades, the EEG has proved to be an important clinical tool for diagnosing and monitoring the central nervous system regarding normal or pathological conditions. For instance, sleep staging based on the EEG has been applied to the evaluation of sleep disorders.

Frequency is one of the important features of EEG waveforms. The EEG rhythmic bands were classified as follows: delta band (0.8 ~ 3.9Hz), theta band (3.9 ~ 7.8Hz), alpha band (7.8 ~ 13.3Hz), and beta band (13.3 ~ 25.0Hz). In our study, we first utilized the spectral contents to characterize and stage the meditation EEG. Method of spectral analysis is based on the short-time Fourier transform (STFT). In our investigation, we occasionally discovered the possible correlation between perception of the inner light and the EEG alpha blocking. A series of experiments were thus performed. More than 60 experienced Zen-Buddhism meditators have been examined in the period from October of 1999 to August of 2003. The experiment continues.

The search for physical and psychological correlates of meditation has centered essentially on three methods: Yoga in India, Transcendental Meditation (TM) in the United States, and Zen Buddhism in Japan. 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 smooth, deep, and quiet, and 2) guarding some important *apertures* like the Zen Chakra (inside the third ventricle), the Wisdom Chakra (corpora quadrigemina), and the Dharma-eye Chakra (hypophysis). Figure 1 illustrates the locations of these Chakras. Gradually, the human life system enters a unique status in harmony with the nature and the universe (called "the unification of heaven, earth, and human"). In the past decade, the Zen-Buddhist meditation, as an unconventional therapy, has proved efficacious for many chronic diseases, infections, and even some malignant tumors. Consequently, more people began to practice the Zen-Buddhist meditation in Taiwan. It aroused our attention to the EEG investigation on the Zen-Buddhist disciples. New findings have been continuously observed and reported (Lo et al., 2003).

Alpha waves usually occur during relaxed wakefulness with eyes closed. When opening the eyes, occipital alpha blocking normally follows. This phenomenon has been well observed and accepted as a convention in EEG research. Investigators accordingly deduced that the occipital alpha rhythm blocking is associated with increased visual attention. However, the mechanism at the neuronal level is still unknown because there are still uncertainties about the origin and neurophysiological significance of the alpha rhythm.

Biological mechanism of meditation model:

By seeking Zen, one is actually seeking the true energy of life. The only entity being promulgated in the Zen-Buddhism Sect is the truth, the wisdom, and the power of Zen in nature. Based on the essence of orthodox Zen Buddhism, we hypothesize that its pivotal technique of meditation can be comprehended via the *resonance* phenomenon.

In a series RLC electrical circuit, the input sinusoid is amplified the most when its frequency equals the resonance frequency of the circuit. No resonance occurs in the physiological, mental, conscious, or subconscious states due to the existence of selfhood. To be in resonance with the inner light, disciples of the Zen-Buddhism Sect spend years preparing themselves for the moment of resonance. One of the preparations, for instance, involves transcending the physiological habituation. The first step is to switch the breathing habit from chest to abdominal breathing. Then by guarding some important *apertures*, the *qi*-energy starts penetrating, from the corpora quadrigemina (the Wisdom Chakra), through the pineal gland (Figure 1), bridging the energy passage between cerebellum and cerebrum. Gradually, the human life system enters a unique status in harmony with the nature and the universe (called "the unification of heaven, earth, and human"). The physical body will change its constitution and, thus, become totally free from diseases.

Experimental protocol and setup:

The subjects of this study are divided into two groups: Zen-Buddhist practitioners (experimental subjects) and non-practitioners (control subjects). The EEG signals were recorded by a 30-channel SynAmps amplifiers (manufactured by NeuroScan, Inc.), using an electrode array with a common linked-mastoid (MS1-MS2) reference according to the international 10-20 method. Figure 2 displays the recording montage. The signals were sampled at 200 Hz and filtered at 0.1-50Hz. Experimental subjects were asked to meditate for 30-35 minutes. Controls were asked to sit and rest quietly with their eyes closed for the same period without falling asleep. Each session of EEG recording lasted 45 minutes, including the first and the last 5-minute background EEG recording (in normal relaxed position) and the mid 30-minute meditation EEG recording. During the meditation session, the subject sat, with eyes closed, in the full-lotus or half-lotus position, putting each hand on the unilateral lap (Figure 3). Both hands formed a special mudra (called the Grand Harmony Mudra). The subject focused on the Zen Chakra and the Dharma Eye Chakra (also known as the "Third Eye Chakra") in the beginning of meditation till he or she transcended the physical and mental realm. The Zen Chakra locates inside the third ventricle, while the Dharma Eye Chakra locates at the hypophysis (Figure 1).

Methods and algorithms for EEG analysis—dimensional analysis and complexity index:

Let $\mathbf{X}=\{\boldsymbol{X}_i\}_{i=1}^{N}$ be the set of points on the EEG trajectory, where $\boldsymbol{X}_i$ is an *n*-dimensional point constructed from (1) the single-channel EEG, or (2) the *n*-channel EEG signals (Lo & Chung, 2000). In the single-channel case, the *n*-dimensional phase-space point $\boldsymbol{X}_i$ is constructed according to the Takens (1981) embedding theory: a smooth map from the time series (e.g., EEG) $\{x[i],\ i=1,\ \ldots,\ N+(n-1)\tau\}$ to the phase-space trajectory $\mathbf{X}=\{\boldsymbol{X}_i=(x[i],x[i+\tau],\ldots,x[i+(n-1)\tau])\}_{i=1}^{N}$ preserves some of topological invariants of the original system. Here τ represents the time delay in number of samples.

For each point in the set $\mathbf{X}$ (e.g., $\boldsymbol{X}_i$), a *K*NN hypersphere is determined and formed by the *K*'s nearest neighboring (NN) points $\{\boldsymbol{V}_{ij}\}_{j=1}^{K}$, $\boldsymbol{V}_{ij}\in\mathbf{X}$ and $\boldsymbol{V}_{i1}=\boldsymbol{X}_i$. The $\boldsymbol{X}_i$ is called the seed point of the *i*th hypersphere. Inside the *i*th hypersphere, the largest distance to the seed point $\boldsymbol{X}_i$ is:

$$d_{i,K\mathrm{NN}} = \left\| \boldsymbol{V}_{iK} - \boldsymbol{X}_i \right\| \tag{1}$$

where the operator $\|\cdot\|$ evaluates the Euclidean distance. It was reported (Lo & Chung, 2000) that

$$\frac{E\{d_{(K+1)\mathrm{NN}}\}}{E\{d_{K\mathrm{NN}}\}} = 1 + \frac{1}{Kn} \tag{2}$$

where $E\{d_{K\mathrm{NN}}\}$ is the first order moment of $d_{K\mathrm{NN}}$, the Kth NN distance of any hypersphere in **X**. Thus, we proposed quantifying the global waveform complexity of multi-channel EEG by estimating the complexity index δ as follows (Lo & Chung, 2000):

$$\delta = \frac{1}{K}\left(\frac{\overline{d_{(K+1)\mathrm{NN}}}}{\overline{d_{K\mathrm{NN}}}} - 1 \right)^{-1}, \tag{3}$$

where $\overline{d_{(K+1)\mathrm{NN}}}$ and $\overline{d_{K\mathrm{NN}}}$ are the average of $d_{i,(K+1)\mathrm{NN}}$ and $d_{i,K\mathrm{NN}}$, respectively, for i=1, …, N. To obtain a reliable estimate of δ, we normally average the δ's over a moderate range of K's to obtain the final estimate. The average δ is denoted by $\overline{\delta}$.

Although Eq.(3) can be easily implemented, a large portion of computer time is spent on searching for the KNN and (K+1)NN distances. Undoubtedly, computer time required by the algorithm implemented in this manner is highly dependent on the values of K and N. A large K costs more effort in the competition process. A large N indicates a large number of distances to be computed.

The authors proposed an approach that does not require computing all the inter-point distances and reduces the exhaustedly sorting process (Lo & Chung, 2001). The approach mainly adopted the eigenfunction and principal-axis analysis. Let [**X**] be an $N\times n$ matrix with its ith row vector representing the ith n-dimensional point $\boldsymbol{X}_i$ on the EEG trajectory. The eigenvector associated with the largest eigenvalue of the covariance matrix of [**X**] is denoted by [**Φ**], a $1\times n$ row matrix. And $\|\Phi\|$=1. Then the transformation [**Y**]=[**X**][**Φ**]$^{\mathrm{T}}$ results in an $N\times 1$ column matrix containing N scalars y_i, i=1, …, N on the principal axis (the largest eigenvector). As a result, the inter-point distances of $\boldsymbol{X}_i$: d_{ij}, j=1, …, N are mapped to

$$\rho_{ij} = \left\| y_j - y_i \right\| = \left\| (\boldsymbol{X}_j - \boldsymbol{X}_i)\Phi^{\mathrm{T}} \right\|. \tag{4}$$

Using ρ_{ij} as reference, the sorting process for determining the $d_{i,K\mathrm{NN}}$ and $d_{i,(K+1)\mathrm{NN}}$ becomes less laborious. Details of implementation were given in (Lo & Chung, 2001).

Methods and algorithms for EEG analysis—AR model and subband filtering:

The method proposed is focused on monitoring the time-varying characteristic frequency in meditation EEG. The AR model is applied to the subband component to quantify the characteristic frequency. Consider that the EEG signal, $x[n]$, is generated by an autoregressive (AR(p)) process driven by the unit-variance white noise [28]. A pth order all-pole model is formulated by

$$x[n] + \sum_{k=1}^{p} a_p[k]x[n-k] = w[n], \quad (5)$$

where p is the order of the AR model. Based on this model, the spectrum of the EEGs can be obtained if the coefficients $a_p[k]$ are known. A number of techniques have been proposed to estimate parameters $a_p[k]$. We apply the autocorrelation method in which the AR coefficients $a_p[k]$ are determined by solving the autocorrelation normal equations

$$\begin{bmatrix} \gamma_x[0] & \gamma_x^*[-1] & \cdots & \gamma_x^*[-p] \\ \gamma_x[1] & \gamma_x[0] & \cdots & \gamma_x^*[-p+1] \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_x[p] & \gamma_x[p-1] & \cdots & \gamma_x[0] \end{bmatrix} \begin{bmatrix} 1 \\ a_p[1] \\ \vdots \\ a_p[p] \end{bmatrix} = \begin{bmatrix} \varepsilon \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \quad (6)$$

where ε is the modeling error and $\gamma_x[k]$ is the estimated autocorrelation function defined below:

$$r_x[k] = \begin{cases} \dfrac{1}{N} \sum\limits_{n=0}^{N-|k|-1} x[n]x[n+|k|], & |k| \le N-1, \\ 0 & \text{otherwise}, \end{cases}. \quad (7)$$

As addressed previously, a higher model order (for example, p ranges from 6 to 14) is normally required to better estimate the low-frequency component in EEG. According to (7), the coefficients of AR(6) model are determined by $\{\gamma_x[k] \mid 0 \le k \le 6\}$. As demonstrated in Table 1, AR(6)'s coefficients $\gamma_x[0] \sim \gamma_x[6]$ for θ and Δ rhythms are too close to distinguish between each other, whereas the coefficients for α and β exhibit significant deviation.

In fact, increasing the model order up to p=12 even cannot discriminate Δ rhythm from θ rhythm. The dominant pole pair for Δ and θ modeled by AR(12) are $0.964\angle\pm0.131$ and $0.959\angle\pm0.129$, respectively, which results in a close estimate of the spectral frequencies (symbol '$\angle$' denotes the phase in radian). In addition, the computational time required by AR(12) becomes quadruple, in compared with that for AR(6).

Downsampling process makes the AR modeling better characterize the low frequency activities. This is revealed by the AR(6)'s coefficients estimated for Δ and θ rhythms downsampled by 8:

$$\gamma_x[k]_\Delta: \{1.00, 0.48, -0.18, -0.48, -0.39, -0.03, 0.06\}, \quad (8a)$$

$$\gamma_x[k]_\theta: \{1.00, -0.16, 0.26, 0.06, -0.42, 0.02, -0.23\}. \quad (8b)$$

Moreover, according to Gabor's uncertainty principle, downsampling operation improves frequency resolution that is desired for the narrow-band EEG. We accordingly employ the subband-filtering scheme prior to the frequency analysis by AR modeling.

In summary, EEG signals are firstly decomposed into different subband components by downsampling and filtering. Then the characteristic frequency (root frequency) of each subband component is estimated by AR(2) model. The entire scheme is called the *Subband-AR EEG Viewer*. The *Subband-AR-EEG Viewer* can be illustrated by the tree-structural filter bank. In the

Subband-AR EEG Viewer, a linear-phase lowpass FIR filter $H(z)$ with cutoff frequency 30Hz is used as an anti-aliasing filter before the downsampling operation. Then the AR(2) model is applied to the decimated signal. The filtering-and-downsampling process is repeated until the equivalent cutoff frequency equals 1.875Hz.

Differing from the wavelet decomposition, the *Subband-AR-EEG-Viewer* only employs the lowpass linear-phase filter. A nonlinear-phase filter frequently employed in the wavelet analysis (Vaidyanathan 1993) will distort the temporal information of EEG and consequently affect the AR model coefficients estimated by the autocorrelation method.

The *Subband-AR-EEG-Viewer* structure can be rearranged as the one shown in Figure 4, which is a six-channel filter bank with two's-power decimation ratios.

The cutoff frequencies of $H_1(z)$, …, $H_5(z)$ are, respectively, 30Hz, 15Hz, 7.5Hz, 3.75Hz, and 1.875Hz (sampling rate: 200Hz).

Note that the cutoff frequencies approximate the upper boundaries of the four well-known EEG rhythms— β (13~30Hz), α (8~13Hz), θ (4~8Hz), and Δ (below 4Hz). Therefore, changes of the characteristic frequency in meditation EEG can be traced by quantifying the root frequency (f_r) of each subband filtered component. For example, when f_r's of $output_1$, $output_2$ and $output_3$ are all within the range 8~12 Hz, the dominated pattern of this windowed segment is identified, to a great degree, as the α rhythm. When f_r's of $output_1$ and $output_2$ are greater than 15Hz and f_r of $output_4$ is between 4Hz and 7Hz, the particular segment most likely contains the θ intermixed with β rhythm.

After the subband decomposition, the AR(2) model coefficients are computed. An AR(2) model can be expressed as

$$x[n] + a_2[1]x[n-1] + a_2[2]x[n-2] = w[n]. \quad (9)$$

The model coefficients are directly computed by

$$a_2[1] = -\left(\frac{r_x[1]}{r_x[0]}\right) + \left(\frac{r_x[1]}{r_x[0]}\right)\left(\frac{r_x[0]r_x[2] - r_x[1]^2}{r_x[0]^2 - r_x[1]^2}\right), \text{ and} \quad (10)$$

$$a_2[2] = -\left(\frac{r_x[0]r_x[2] - r_x[1]^2}{r_x[0]^2 - r_x[1]^2}\right), \quad (11)$$

where $\gamma_x[k]$ is the autocorrelation function estimated by (3).

The characteristic frequency, also called the "root frequency," of $output_i$ can be estimated from the phase of the pole, or the root of the model equation (9) expressed in frequency domain. After obtaining the model coefficients, the conjugated pole pair are

$$-\frac{a_2[1]}{2} \pm j\frac{\sqrt{4a_2[2] - a_2{}^2[1]}}{2}. \quad (12)$$

Therefore, the root frequency f_r can be formulated as

$$f_r = \sin^{-1}\left(\frac{\sqrt{\frac{4a_2[2]-a_2^2[1]}{4}}}{\sqrt{a_2[2]}}\right) = \sin^{-1}\left(\sqrt{1-\frac{a_2^2[1]^2}{4a_2[2]}}\right) \approx \sqrt{1-\frac{a_2^2[1]}{4a_2[2]}} \,. \tag{13}$$

Because the root frequency is much smaller than the sampling frequency, the result of $\sin^{-1}x$ can be approximated by x. For example, the α rhythm having a higher frequency of 12Hz results in a normalized radian frequency of 0.12π (assume f_s = 200Hz). The approximation only causes a 2.35% deviation from the true value. Note that $output_2$~$output_6$ are the results of downsampling (Figure 4), the root frequency $f_{r,i}$ should be further divided by 2^i. According to equations (10) to (13), root frequency of each subband component depends on $\gamma_x[0]$, $\gamma_x[1]$, and $\gamma_x[2]$.

Tracking the root frequency of each subband component provides an efficient way to illustrate the time evolution of characteristic frequency in meditation EEG. The following section presents two algorithms for the EEG feature extraction and the signal segmentation based on the ideas and methods introduced in this section.

IV. RESULTS

(A) Alpha-blocking phenomenon in meditation EEG:

Bursts of high-frequency beta (above 20Hz) are observed when the meditators enter into deep meditation. In our meditation EEG recordings, a few subjects even had significant beta activities since the beginning meditation. This phenomenon arouses our interest in further investigating the potential mechanism. After performing a few studies on different subjects, however, we noted a significant correlation between perception of the inner light and the alpha blocking. Subject A, a healthy 48-year-old man, had been practicing the orthodox Zen Buddhism for more than 11 years. While meditating with eyes closed, his EEG was mainly characterized by the low alpha (8~9 Hz) activities. A close examination showed that the tiny, high-frequency beta jiggling mingled in the alpha rhythms. When subject A signaled the event of perceiving the light, alpha blocking occurred and the EEG turned into low-amplitude beta (Figure 5). Subject B was a healthy 40-year-old female who had been practicing the Zen-Buddhism meditation since 1994. For more than five years, she had never fallen ill. Like most Zen-Buddhism practitioners, she had an appearance and physiological status ten-year younger than her age. Her EEG in meditation switched between low-frequency (≈8Hz), high-power alpha and global beta activities, with larger amplitude in the frontal regions (F3, F4). As illustrated in Fig. 4, there always occurred the alpha blocking in succession to the signaling of perceiving the light (Figure 6).

Our experiment encountered one major difficulty— missing signals from the subjects. It is comprehensible since the subject at the meditating state beyond normal consciousness often 'forgets' the experimental protocol. In the circumstances, the EEG events cannot be correlated with the meditating process via subjective expression.

In the second part of this experiment, EEG changes under *blessing* is discussed. *Blessing* is mostly comprehended as the benediction, ritual, or manner conveying best wishes to someone. *Blessing* in the orthodox Zen Buddhism, on the other hand, indicates a substantial benefaction from the master. A true master in the orthodox Zen Buddhism is required to attain the Buddhahood Trinity— full attainment of Buddha’s three bodies, the emanation body (Nirmanakaya 應化身), the truth body (Dharmakaya 法身), and the blessedness body (Sambhogakaya 報身、佛

身). With the true energy (light) of life in nature, he is thus able to help disciples.

In our *blessing* experiment (Lo, Huang, and Chang 2003), master Miao Tien of the Zen-Buddhism Sect was invited to perform the *blessing*. It had been reported that blessing from master Miao Tien had cured many people. To avoid the possibility of placebo effect, the subjects did not know that they were to be blessed during the EEG recording. Master Miao Tien was not in the same room where the experiment was conducted. The mechanism of performing far-field *blessing* is still unknown from the scientific viewpoint. As stated by the Zen master, it was the truth body (Dharmakaya) that performed the *blessing*, and this *blessing* energy was bestowed upon the true self. Both the experimental group (Zen-Buddhism practitioners) and the control group followed the same procedure: they were asked to sit, with eyes closed, in the normal relaxed position for 30 minutes. The EEG under blessing was compared with the normal background EEG.

To illustrate the EEG evolution during the entire session, the running Fourier spectral power based on short-time Fourier transform (STFT) was analyzed and percentage of power in each rhythmic band was depicted by different gray shade (Figure 7). The STFT was computed with a 2-second frame, shifted with a step of 1 second each time. The result was filtered twice by a lowpass moving averager of order 11 to smooth the jiggling. As shown in Figure 7, significant alpha blocking was observed in experimental subjects (C and D) during the *blessing* period. This alpha blocking phenomenon was highly correlated with the fact that the subjects *saw* the light, according to our post-experimental interview. In the blessing period, there accompanied the slower rhythmic activities (theta and delta). The large power of low-frequency EEG rhythms prevails over the small-amplitude beta so that the emergence of beta rhythm cannot be discriminated in the running power-percentage analysis. Apparently, there was no significant change in EEG evolution in the non-meditating control subject (E) under *blessing*. Their EEGs contained a large proportion of alpha power in the entire record.

The above experiment somehow reveals the essence of Zen-Buddhism practicing— one can only sense the light of truth after years of preparation for eventually being in resonance with the inner light. On the way of preparation, the human body itself changes its characteristics and is gradually adjusted to a state of being able to perceive this non-physical, spiritual power of *blessing*.

(B) Meditation EEG scenarios:

Meditation EEG scenarios—nonlinear dynamics and complexity index:

The meditation EEG records collected from the Zen-Buddhist disciples exhibit some characteristic features that have been constantly observed. Figure 8 profiles those features from 5 meditators who appear certain pattern frequently. In Figure 8(a), the top tracing characterizes the deep meditation (also called '*samadhi*' or '*transcendence*') EEG that may be correlated with the Alaya (eighth) conscious state. The EEG at this stage was found to be featured by the "silent" pattern (to be symbolized by Φ in this paper). The second tracing, mainly composed of fast β rhythm with small amplitude, was observed mostly when the meditator entered into a peaceful, body-mind unified, and somehow beyond normal consciousness states. The slow α (4^{th} tracing) relates to the mind-concentrating status of the sixth conscious state. West reported their finding of slower α (8~10Hz) with larger amplitude in the beginning of meditation (West, 1980). In the Zen-Buddhist practice, meditators normally concentrate their mind on particular Chakra(s) in the beginning to release themselves from flight of the imagination. We found that the EEG of a few subjects at this meditating stage exhibited a large portion of slow α rhythm. As the Zen meditation proceeds, much slower θ and Δ rhythms may appear in some subjects. According to the subjective narration by meditators, they may feel drowsy or enter the seventh consciousness (sub-consciousness). In Figure 8(b), the 2D (two-dimensional) phase trajectories are constructed from the EEG epochs in Figure 8(a) using a delay of 5 samples (0.025 second). Apparently, the silent and β patterns have the phase trajectories of shrinking dynamical extent, yet with higher degree of irregularity. The α trajectory exhibits harmonious orbital patterns with high coherence. Both the θ and Δ trajectories involve dynamics of multi-modes, that is, the system dynamics are governed by two or more nonlinear mechanisms with different degrees of freedom. In Figure 8(b), the θ and Δ trajectories apparently travel different spans in the phase space. This phenomenon is mostly caused by the simultaneous emergence of multiple EEG rhythms, for instance, the Δ accompanied by β rhythm. In the case, outer orbits track the Δ activity, while the inner orbits follow the β rhythm. This phenomenon results in two distinct estimates for the complexity index δ. First, small K indicates that the $d_{i,K\mathrm{NN}}$ (KNN distance), obtained after searching all the orbital points, most likely characterizes orbits of the same attribute. As K becomes large, the $d_{i,K\mathrm{NN}}$, on the other hand, may represent the inter-distance between two orbital points that track different EEG rhythms.

Meditation EEG scenarios—subband-AR-EEG-Viewer for tracking slow α:

Frequency of α rhythm ranges from 8Hz to 12Hz. The slow α is a particular pattern, normally below 10Hz, that is observed in some experimental subjects at the mind-focusing stage of meditation. The *Subband-AR-EEG-Viewer*, designed to track the slow-α, can be reduced to the structure shown in Figure 9(a), with the algorithm illustrated in Figure 9(b). According to analytical reasoning and practical experience, $output_1$ in combination with $output_3$ highly enhances the effectiveness of slow-α detection. Note that the $f_{r,1}$ acts as an index of screening out the high-frequency component, and the $f_{r,3}$ is employed in the classification as a major reference. The algorithm (Figure 9(b)) depicts that slow-α pattern is detected when both root frequencies satisfy the following criteria:

$\underline{f_{r,1}} < 14$Hz, and

8Hz $< \underline{f_{r,3}} <$10Hz.

While only examining $output_1$ (up to 30Hz) with the criterion 8Hz $< f_{r,1} <$10Hz, the model often fails to identify the noise-contaminated slow-α activities. Figure 10 demonstrates the noise-immunization capability of our model. When a pure 9Hz sinusoid (Figure 10(a)) is partially contaminated by a uniformly distributed random noise (Figure 10(b)), the *AR* model does not recognize the noise-contaminated slow-α segment based on the criterion 8Hz$<f_{r,1}<$10Hz (Figure 10(c)). Note that the epoch identified as the slow α is indicated by a black bar above the signal. Result in Figure 10(d) shows that the proposed model successfully detects the slow α under poor environment (SNR=8dB).

To justify the performance, we first analyze a simulated signal of 4-second duration. The signal shown in Figure 11(d) is generated by connecting three short-duration, amplitude-modulated sinusoids, respectively, with frequencies 9Hz, 15Hz, and 5Hz (Figure 11(a)~(c)). The window length is 0.5 second (100 samples), moving at a step of 0.25 second. As shown in Figure 11(d), the algorithm effectively detects the occurrence of slow-α pattern.

Next, the algorithm is applied to the meditation EEGs (channel O1). A 10-second segment shown in Figure 12 is analyzed with the same implementing parameters as which used in Figure 11. A dark bar above the signal indicates the slow-α detected. As shown in Figure 12(a), amplitude variation often affects the recognizability of slow-α. It results in a crack in the first dark bar. On the other hand, a transient slow-α may be of little significance. We thus design a post-processor to further refine the result. It removes segments of duration shorter than 0.3 second and fuses a crack smaller than 0.3 second (Figure 12(b)).

Detection of specific EEG patterns is important in identifying various meditation states. In addition, it may serve as a preprocessing stage in such tasks like the EEG segmentation or interpretation. Based on the *Subband-AR-EEG-Viewer*, we devised a particular scheme for meditation EEG interpretation. Details are illustrated below.

Meditation EEG scenarios—Subband-AR-EEG-Viewer for long-term interpretation:

Changes of the characteristic frequency in meditation EEG may be a key feature for understanding various states of consciousness during meditation. We therefore develop a logical strategy implemented in a computerized algorithm to segment the EEG into sections with different frequencies. The results illustrated by a running gray-scale chart indicate the evolution of characteristic frequency during meditation. In the following study, we present the result of interpreting the meditation EEG based on five spectral features frequently observed during meditation. The five features include: (1) slow waveform intermixing with high-frequency rhythms (symbolized by 'χ'), (2) Δ, (3) θ, (4) α, and (5) β. The χ feature mostly appears at the transition from one EEG rhythm to another. To provide a long-term legible illustration, five spectral features are displayed by different grays. The gray tones from the darkest to the brightest colors indicate, respectively, the χ, Δ, θ, α, and β feature. In this task, the structure of *Subband-AR-EEG Viewer* can be reduced to that shown in Figure 13.

The algorithm examines each windowed segment to check the following criteria in order:

Criterion-χ: $\underline{f_{r,3}}$<7Hz<$\underline{f_{r,1}}$ and $|\underline{p_3}|$>0.7;

Criterion-Δ: $\underline{f_{r,1}}$<7Hz and $\underline{f_{r,4}}$<3.5Hz;

Criterion-θ: $\underline{f_{r,1}}$<7Hz;

Criterion-α: $\underline{f_{r,1}}$<14Hz and 7Hz<$\underline{f_{r,3}}$;

Criterion-β: 7Hz<$\underline{f_{r,1}}$;

where $\underline{p_3}$ is the AR(2)'s pole of $output_3$. The criteria checkup is ordered according to a sound logic realizing the subband filtering scheme. The root frequency $f_{r,1}$ is used to differentiate between 0~7Hz and 7~30Hz EEG bands, while the $f_{r,3}$, $f_{r,4}$ and $|p_3|$ are employed in the subsequent discrimination process. The length of p_3 can be considered as an indication of the significance of the root frequency. Because the χ wave represents an intermixed signal composed of both low- and high-frequency components, we impose restrictions on the range of $|p_3|$ to ensure the significance of the low frequency component.

To verify the effectiveness of feature recognition, the algorithm is firstly applied to a simulated signal. As displayed in Figure 14(e), the signal is constituted by connecting five segments of Δ, θ, χ, α, and β patterns, respectively. Assume the sampling rate is 200Hz. This signal can be simulated by the pole placement method, that is, placing each pole in the corresponding frequency band and adding Gaussian noise. Transition from θ to β normally results in such a compound pattern like χ. The running gray-scale chart (Figure 14(e)) above the simulated sequence successfully signals the temporal patterns.

The above simulation demonstrates the feasibility of the model and algorithm in Figures 8 and 9 for automatically identifying different EEG rhythms and revealing its time-varying schema. In empirical data, more complex rhythmic patterns involved may result in discrepancy between experienced EEG interpreters. Methodology development thus focuses on reliable recognition of some key features in meditation EEG analysis. Figure 15 demonstrates the robustness of the *Subband-AR-EEG Viewer* for identifying even the little jittering of β rhythms embedded in the high-amplitude slow activity.

When applied to the long-term meditation EEG, this method is particularly robust for automatic interpretation with no need to determine the implementing parameters. Figure 16 displays three running gray-scale charts for two experimental subjects (Figures 16(a) and (b)) and one control subject (Figure 16(c)). The error rate is approximately 8.7% in comparison with the results of naked-eye examination by an experienced EEG interpreter. Both meditators have been practicing the Zen-Buddhist meditation for more than eight years. Subjects of the control group sat in a normal, relaxed position with eyes closed. During the 10-minute meditation session, two meditators exhibited different meditation scenarios. Meditation EEG of subject 2k1019p is apparently dominated by β rhythm, sometimes transforming into short-duration α's. According to the post-experimental interview, the subject did not always stay in the Alaya consciousness and occasionally got back to normal consciousness. The chart in Figure 16(a) evidently reveals this scenario. In Figure 16(b), subject 2k0830a exhibited a large portion of χ activities. In our meditation EEG study, EEG signals of some meditators indeed were found to be characterized by large-amplitude, slow-drifting rhythms interwoven with high-frequency tiny jiggles. Meditators with this kind of EEG characteristics normally have their meditation process wandering among normal consciousness, subconsciousness (subliminal consciousness), and Alaya consciousness (Lo, Huang, Chang 2003). Compared with the experimental group, EEG's collected from the control subjects are normally dominated by α rhythm, as illustrated in Figure 16(c). Note that this subject drowsed in the experiment, resulting in occurrence of θ and Δ rhythms.

(C) Spatio-temporal characteristics of meditation EEG:

In (Lo and Huang 2004), we demonstrated the running $\bar{\delta}$ chart analyzed for selected 8-channel EEGs, including channels F3, F4, C3, C4, P3, P4, O1, and O2 for three experimental subjects and one control subject . We notice that the beginning five-minute EEGs are pretty much the same for the control subjects and the group-M2 meditators on the occipital brain region. That is, α-rhythm dominates the EEG activities. This phenomenon is almost spatially unbiased for some control subjects. The α-rhythm appears at all the recording sites on the scalp, without limiting to the occipital region. Nonetheless, group-M2 meditators exhibit lower complexity in brain dynamics corresponding to the slow (θ+Δ) activities. The Φ/β-dominated EEG of groups M2 and M3 is evident in the 8-channel $\bar{\delta}$ charts. Group-M2 EEG, yet, reveals intermittently emergence of (θ+Δ) (dark gray) and α (mid gray) activities on the background Φ/β. The 8-channel $\bar{\delta}$ chart of group M2 shows higher $\bar{\delta}$'s on the occipital and parietal regions, indicating the occurrence of significant Φ/β. Group-M3 subjects have an extraordinary EEG during the entire meditation session—— consistent Φ/β activities spreading all over the scalp. Brain dynamics of high dimension and high complexity might be referred to the *transcendental* state of consciousness. After twenty-minute recording, the $\bar{\delta}$ charts differ a lot among the four groups. The gray-scale chart for the group-C1 control subjects remains about the same. Group-M1 EEG basically is composed of the same rhythmic patterns, yet with increasing proportion of α rhythms on the parietal and occipital regions. Group-M2 subjects enter into the high-complexity brain dynamics (Φ/β), as that of group M3, all over the scalp during the last few minutes.

Note that the group-M1 meditators were fully awake though a large amount of θ and Δ rhythms appeared. We attempt to hypothesize the occurrence of slow waves according to the quintessence and the ultimate aim of the orthodox Zen-Buddhist practice— attaining an eternal state called the *Buddhahood* by firstly proving the most original true-self that embeds the light of the supreme wisdom, the noumenal energy, and the natural powers. Gradually, the human life system enters a unique status in harmony with the nature and the universe. The physical body thoroughly changes its constitution and, thus, becomes totally free from diseases. The meditators in group M3 are special. Their EEGs have been steady all the way through the meditation course. Particularly, α rhythm even has never appeared since the beginning of meditation. The meditators in this particular group said that their brain and mentality had been totally different from what before practicing the Zen-Buddhist meditation. They are now so calm, serene and peaceful when they are not in use. This status makes the meditators better preserve their mental power and body energy. On the other hand, they perform much better in their work or study because, without the interference from "mental noise," they feel more concentrated.

According to the above illustration, the meditation EEG evidently involves both spatial and temporal information. For investigating the spatial localization, the brain mappings of one-minute averaging $\bar{\delta}$ in Figure 17, reconstructed from the 30-channel EEGs, demonstrate an interesting spatio-temporal phenomenon (Lo and Huang 2004). Control subjects exhibit global α activities in the first and last five-minute intervals. Group M1 begins with a bright-gray mapping and transits into a mid-tone one indicating the occurrence of α rhythm, whereas the brain mapping of group M2 evolves in the reverse course. As for group M3, The mapping further demonstrates the phenomenon of global *quiet* electrical activities in deep, transcendental Zen meditation.

V. CONCLUSION AND DISCUSSION

This work is devoted to the investigation of physiological and mental characteristics of individuals having been practicing the Zen-Buddhist meditation for years. Significance of the work is never overemphasized especially the meditation practice has been proven to benefit mankind, including health, character, life outlook, social morality, etc. In this paper, EEG was measured and analyzed to study, as narrated by the meditators, the unique sensation during meditation or the changes of physiological conditions after years of practice.

Scientific convention developed in the physical world may not allow us to explain every aspect of nature, especially those non-physical, intangible experiences developed during the Zen-Buddhism practicing. Nevertheless, connection between spiritual experience and physical phenomenon can be explored via the medium of human life system. In this article, we report a reasonable hypothesis that bridges the alpha-blocking phenomenon with perception of the inner light of true self. This is one of the experiences discovered by the orthodox Zen-Buddhism practitioners on the way towards unification of physical, mental, and spiritual (true-self) entity. At the onset of this experience, the alpha-dominated background EEG turns into small-amplitude beta rhythm, or becomes flat with its amplitude significantly suppressed. Perceiving the inner light, as stated by the practitioners, makes themselves feel being *blessed* by the inner energy of true self. This kind of experience enables them to remain in a calm, centered, or sometimes ecstasized state of mind. It works like a sudden illumination that releases their mind from the inextricable maze. As a result, they gain a great health after years of practicing. The argumentation proposes that we may promote our health via disclosure of this inner energy. This report provides a new insight into the debate that meditation benefits the physiological, psychological, and mental health.

Note that the Chakras (Figure 1) involved in the perception of inner light locate near the visual perceptive pathway. May we hypothesize that the alpha blocking relates to the visual attention to the inner light? The inference is still primitive since direct validation or detection of the true-self energy is unfeasible in the present scientific and technical circumstances. Nonetheless, the hypothesis is substantially sound based on the instrumentation of human life system that can be maneuvered for corroborating this energy.

Based on the concept of fractional dimension estimation in nonlinear dynamical theory, running measurement of averaged complexity index ($\bar{\delta}$) has been developed and implemented to the long-time meditation EEG to investigate the meditation scenario. Distinct differences were observed between the control and experimental groups. Of particular interest, we observed three different modes (scenarios) in the experimental (meditation) group according to the EEG evolution. These running $\bar{\delta}$ charts somehow correlate with the subjective illustration of their meditation sensation. However, concrete relationship between EEG activity and meditation states (or, various states of consciousness) is still inaccessible because of the fundamental problem of collecting information from the individual under meditation. Substantially speaking, the meditators cannot convey information by any means when they are meditating beyond the physiological and mental state; otherwise, they often will return back to the normal conscious state. Another issue encountered in the meditation EEG research is the effect of "ambiance"—meditators were not able to achieve good-quality meditation in the laboratory compared with meditation quality at the Zen-Buddhist meditation shrine where, described by the disciples, the sacred power of Buddha is bestowed. Many factors involved in meditation study have been continuously disclosed since we began to investigate the Zen-Buddhist meditation in 1999. Nevertheless, scientific curiosity may lead into the exploration of the myths of spiritual realm.

In order to explore the meditation scenario, we also presented a systematic strategy for developing algorithms for automatic EEG interpretation. Based on the concepts of subband filtering and parametric modeling, a generalized computation scheme, called *Subband-AR-EEG Viewer*, can be modified and adapted for different application purposes. With appropriate logic for examining the characteristic frequency, the model can be further reduced to improve computational efficiency without affecting the performance. In addition, the proposed scheme requires no implementing parameter. Another noticeable advantage is its feasibility for real-time, hardware realization and implementation. Since an order-2 AR model is employed, computational load is very light. For the example of slow-α detection, the algorithm involves approximately 3.75N real multiplications (N: number of samples), a significant reduction in arithmetic operations compared with the FFT algorithm for rhythmic analysis.

In these financially stressed times, Zen meditation can be considered an effective means of promoting health of the citizens and reducing the government expenditure on health insurance. According to our survey and statistical analysis of the results, Zen-Buddhist practitioners indeed exhibit better health in both physiological and mental conditions in comparison with the conditions before their practice. Particularly, the data of HIC applications demonstrate an impressively reduction of the average number of clinical visits by the practitioners, that helps the community save an enormous amount of expenditure on health insurance. As a consequence, it could never be overvalued for researchers to make more effort to explore the biological, physiological, mental, and even spiritual phenomena and characteristics of the human life system optimized for years by the Zen-meditation practice.

VI. REFERENCES

Anand, B. K., Chhina, G. S., and Singh, B. (1961). Some aspects of electoencephalographic studies in yogis. *Electroenceph. Clin. Neurophysiol.*, **13**, 452.

Banquet, J. P. (1973). Spectral analysis of the EEG in meditation. *Electroenceph. Clin. Neurophysiol.*, **35**, 143.

Barinaga, M. (2003), Buddhism and neuroscience. Studying the well-trained mind. Science, 302(5642):44-46.

Becker, D. E. and Shapiro, D. (1981). Physiological responses to clicks during zen, yoga, and TM meditation. *Psychophysiology*, **18(6)**, 694.

Bennett, J. E. and Trinder, J. (1977). Hemispheric laterality and cognitive style associated with transcendental meditation. *Psychophysiology*, **14(3)**, 293.

Edwards, L. (2003). Meditation as medicine. Benefits go beyond relaxation. Advances for Nurse Practitioners, 11(5):49-52.

Fields, J. Z., et al. (2002). Effect of a multimodality natural medicine program on carotid atherosclerosis in older subjects: a pilot trial of Maharishi Vedic Medicine. American Journal of Cardiology, 89(8):952-958.

Hebert, R. and Lehmann, D. (1977). Theta bursts: An EEG pattern in normal subjects practicing the transcendental meditation technique. *Electroenceph. Clin. Neurophysiol.*, **42**, 397.

Jevning, R., Wallace, R. K., and Beidebach, M. (1992). The physiology of meditation: a review. A wakeful hypometabolic integrated response. *Neuroscience and Biobehavioral Reviews*, **16**, 415.

Kasamatsu, A. and Hirai, T. (1966). An electroencephalographic study of the zen meditation (zazen). *Folia Psychiatrica et Neurologica Japonica*, **20**, 315King, M. S., Carr, T., and D'Cruz, C. (2002). Transcendental meditation, hypertension and heart disease. Australian Family Physician, 31(2):164-168.

Factor-Litvak, P., Cushman, L.F., Kronenberg, F., Wade, C., Kalmuss, D. (2001). Use of complementary and alternative medicine among women in New York City: a pilot study. Journal of Alternative and Complementary Medicine, 7(6):659-666.

Lo, P.-C., Huang, M.-L., and Chang., K.M. (2003). EEG alpha blocking correlated with perception of inner light during Zen meditation**.** American Journal of Chinese Medicine, 31(4):629-642.

Lo, P.-C. and Chung, W.-P. (2001). An efficient method for quantifying the multi-channel EEG spatial-temporal complexity. *IEEE Trans. BME*, **48 (3)**, 394.

Lo, P.-C. and Chung, W.-P. (2000). An approach to quantifying the multi-channel EEG spatial-temporal feature. *Biometrical Journal*, **42 (7)**, 21.

Lo, P.-C. and Huang, H.-Y. (2004). Investigation of Meditation Scenario by Quantifying the Complexity Index of EEG, submitted to *Nonlinear Dynamics, Psychology, and Life Sciences*.

Pagano, R. R., Rose, R. M., Stivers, R. M., and Warrenburg, S. (1976). Sleep during transcendental meditation. *Science*, **191**, 308.

Stigsby, B., Rodenberg, J. C., and Moth, H. B. (1981). Electroencephalographic finding during mantra meditation (transcendental meditation). A controlled, quantitative study of experienced meditators. *Electroenceph. Clin. Neurophysiol.*, **51**, 434.

Vaidyanathan, P.P. (1993) Multirate systems and Filter Banks, Prentice Hall, Englewood Cliffs, New Jersey NJ.

Wallace, R. K. (1970). Physiological effects of transcendental meditation. *Science*, **167**, 1751.

West, M. A. (1980). Meditation and the EEG. *Psychological Medicine*, **10**, 369.

Williams, P. and West, M. (1975). EEG responses to photic stimulation in persons experienced at meditation. *Electroenceph. Clin. Neurophysiol.*, **39**, 519.

Woolfolk, R. L. (1975). Psychophysiological correlates of meditation. *Arch Gen Psychiatry*, **32**, 1326.

VII. TABLES

Table 1. AR(6) coefficients, $\gamma_x[0] \sim \gamma_x[6]$, computed for Δ, θ, α, and β rhythms.

	$\gamma_x[0]$	$\gamma_x[1]$	$\gamma_x[2]$	$\gamma_x[3]$	$\gamma_x[4]$	$\gamma_x[5]$	$\gamma_x[6]$
Δ	1.000	0.986	0.948	0.891	0.822	0.746	0.665
θ	1.000	0.985	0.946	0.889	0.823	0.752	0.676
α	1.000	0.946	0.792	0.562	0.287	–0.0004	–0.271
β	1.000	0.872	0.553	0.166	–0.155	–0.323	–0.324

VIII. FIGURES

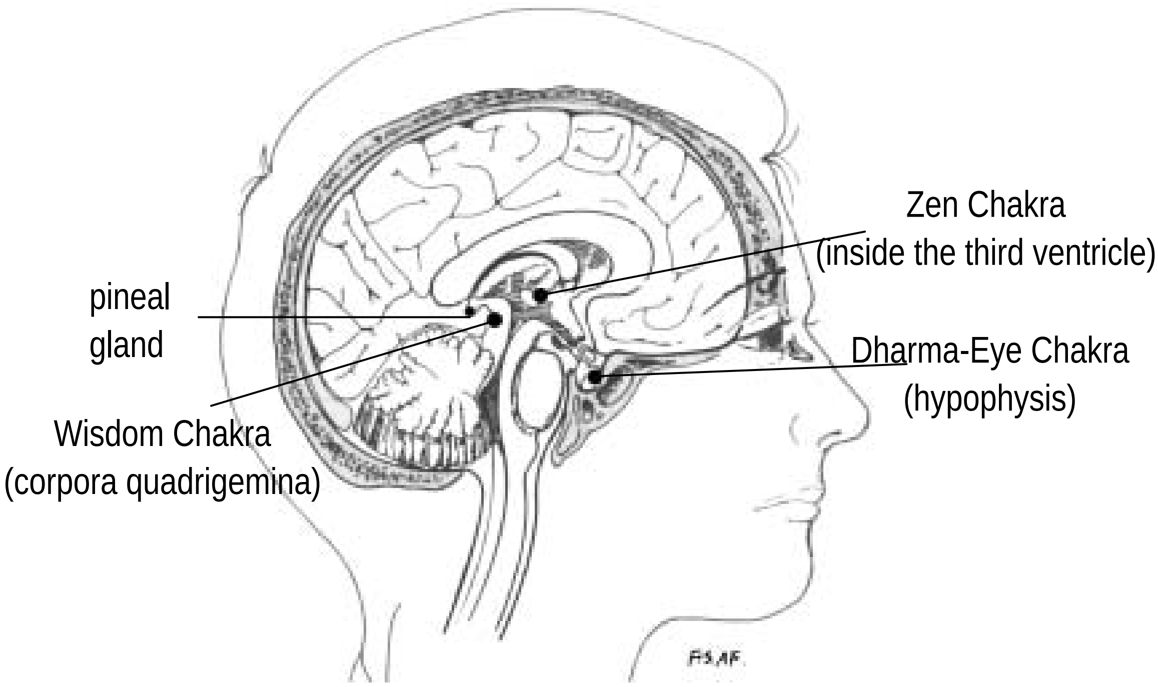


Figure 1 The important chakras inside the head.

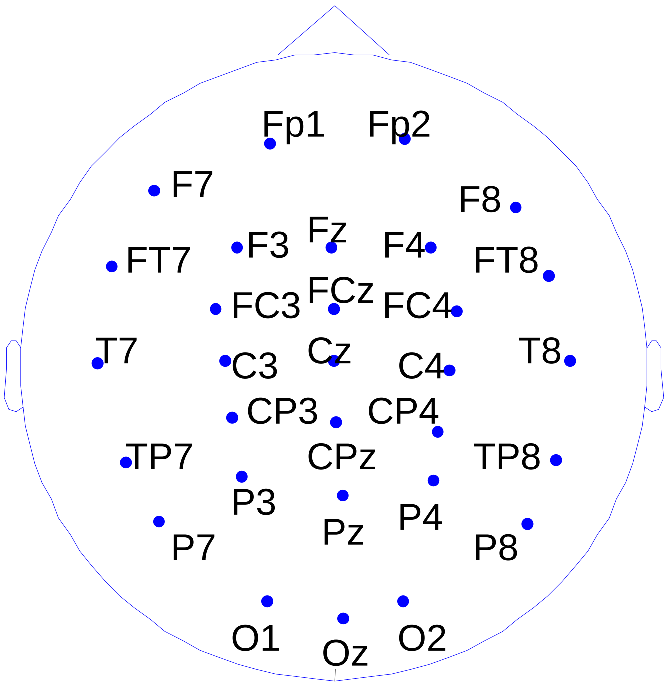


Figure 2 The 30-channel recording montage.

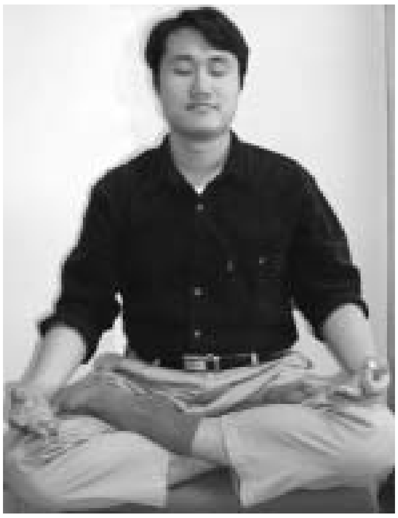


Figure 3 Meditation posture.

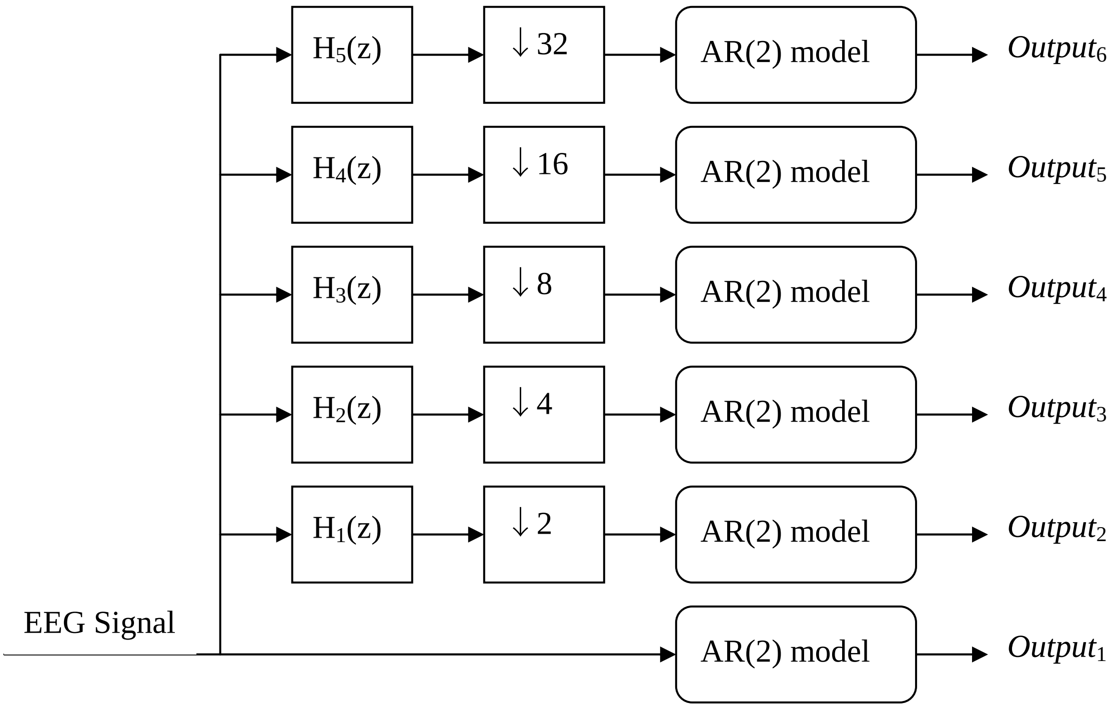


Figure 4 The equivalent six-channel system of the subband filter bank.

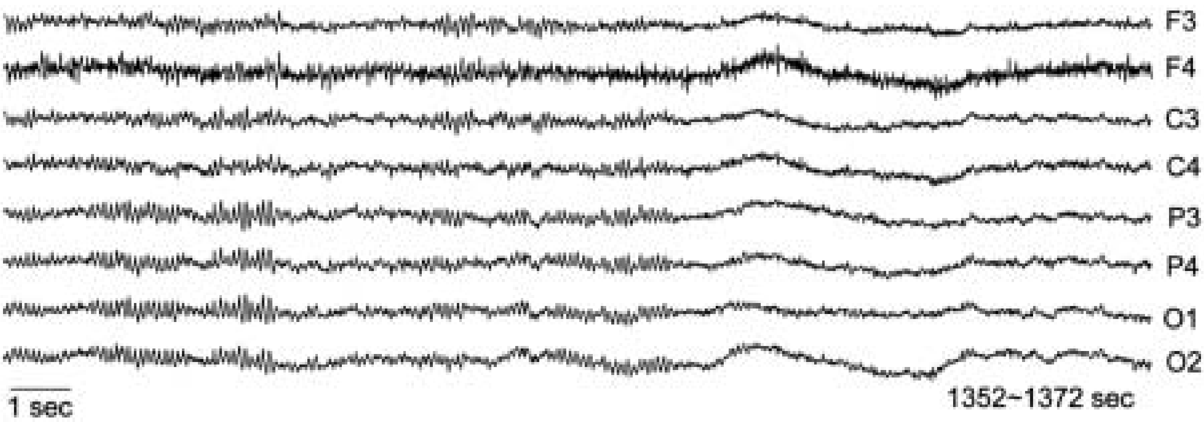


Figure 5 EEG segment of subject A when perceiving the light.

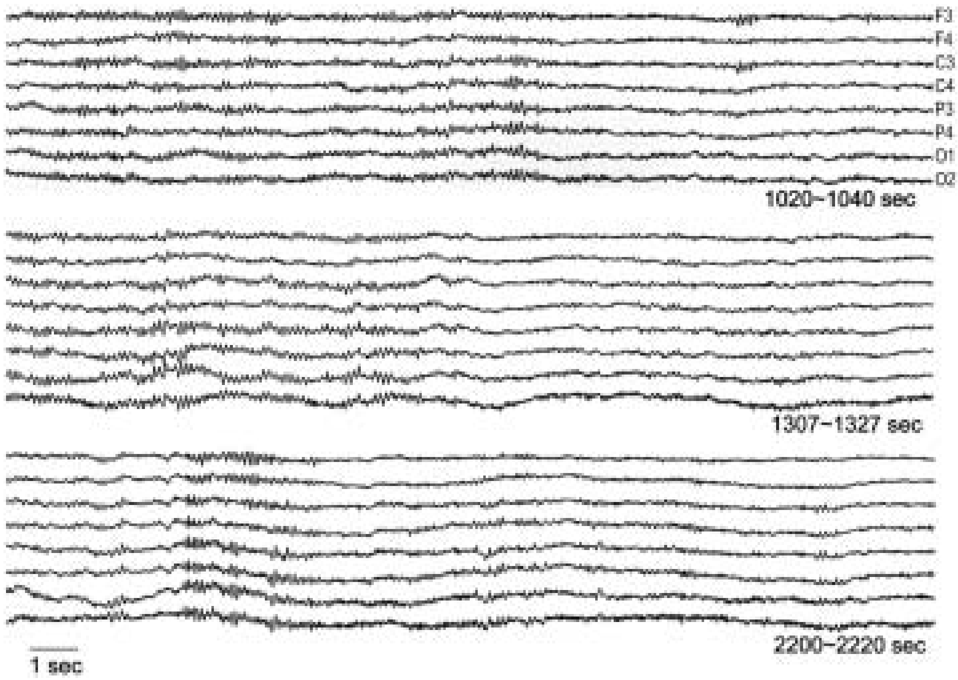


Figure 6 Three EEG segments (subject B) reflecting the effect of perceiving the light.

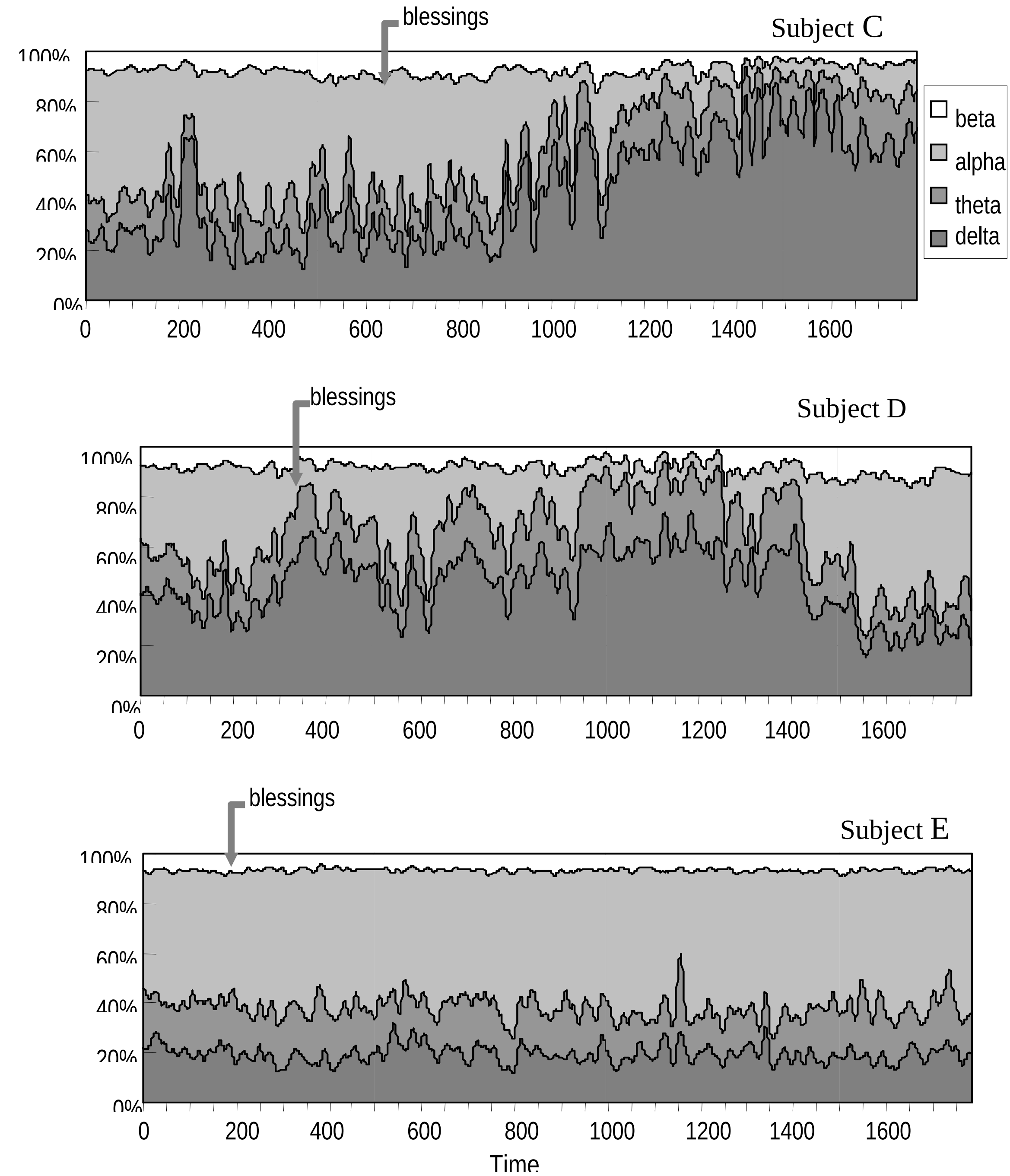
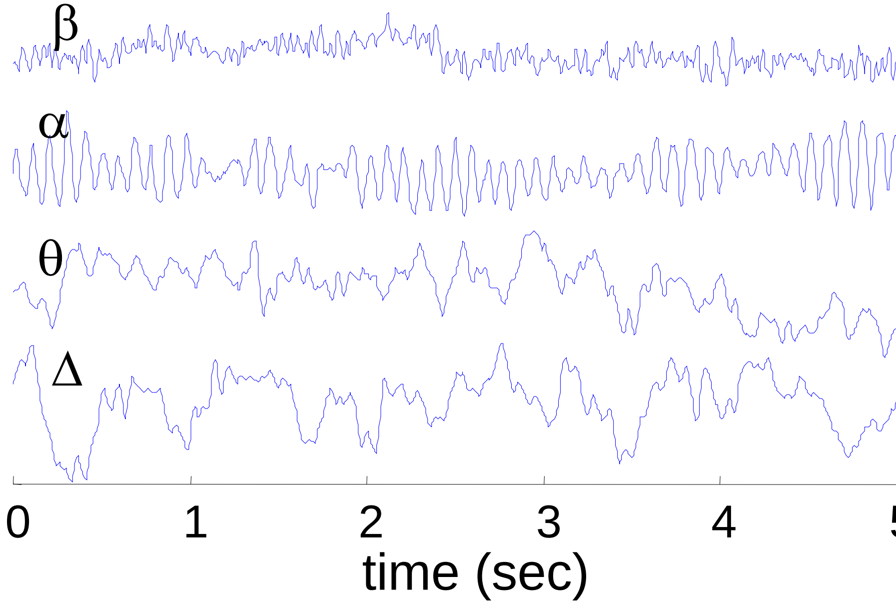
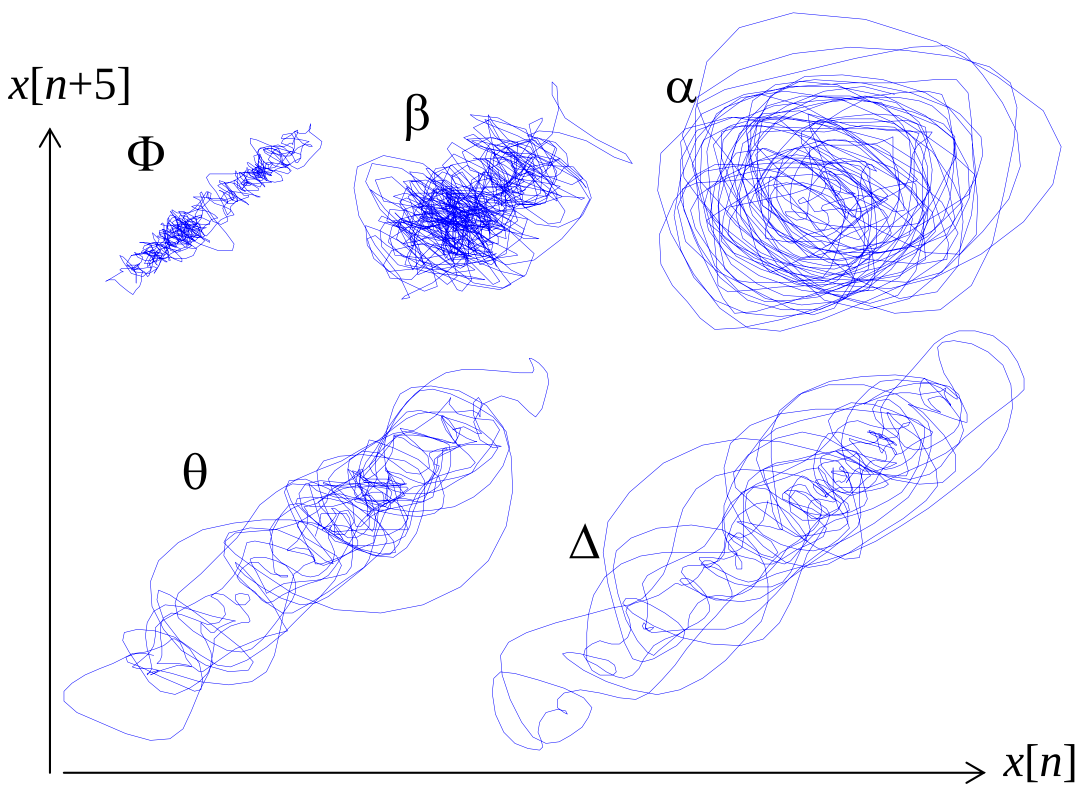


Figure 7 Results of the running power-percentage analysis for the *blessing* EEG data.

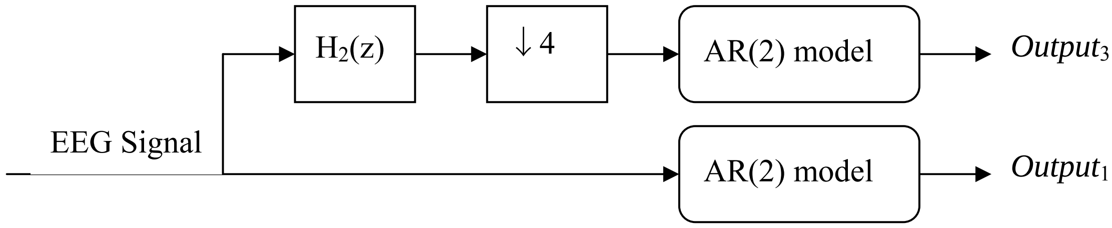


(a)

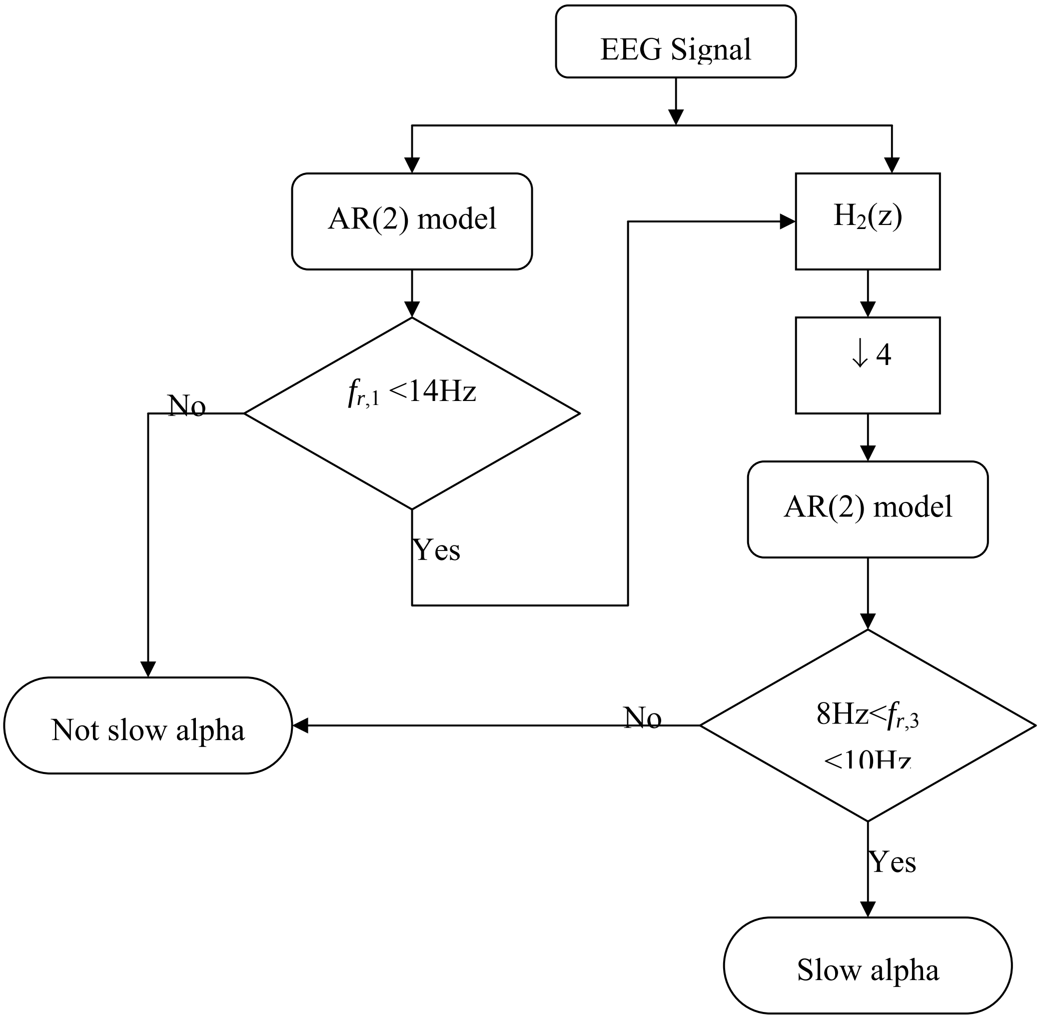


(b)

Figure 8 (a) Meditating EEG patterns and (b) Constructed phase trajectories, (delay=0.025s duration=5s).



(a)



(b)

Figure 9 The subband filter bank modified for slow-α detection, (a) the structure, and (b) the algorithm.

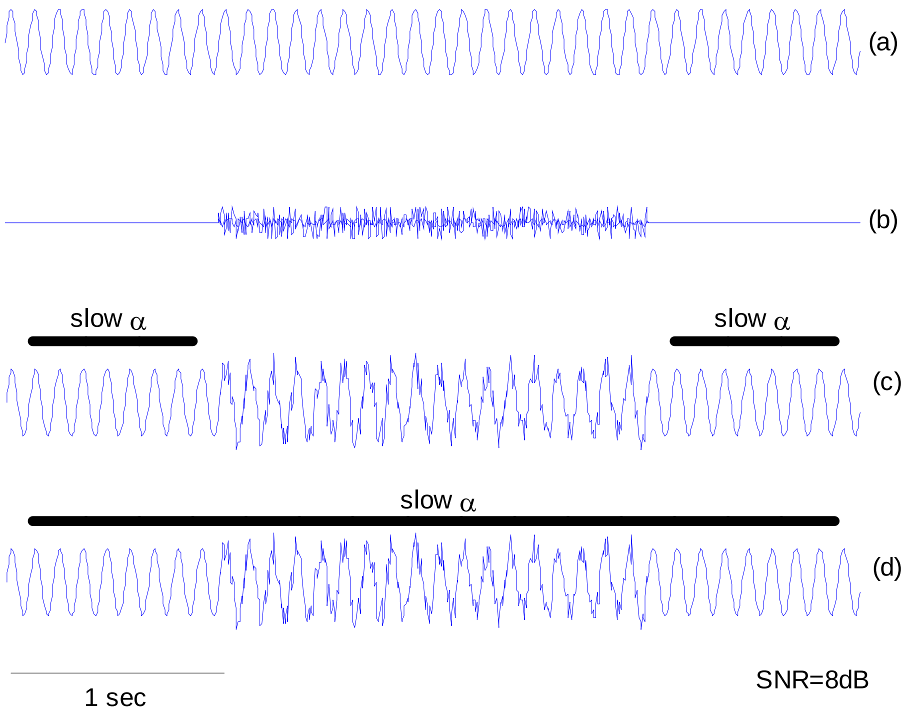


Figure 10 Capability of noise immunization of slow-α detector.

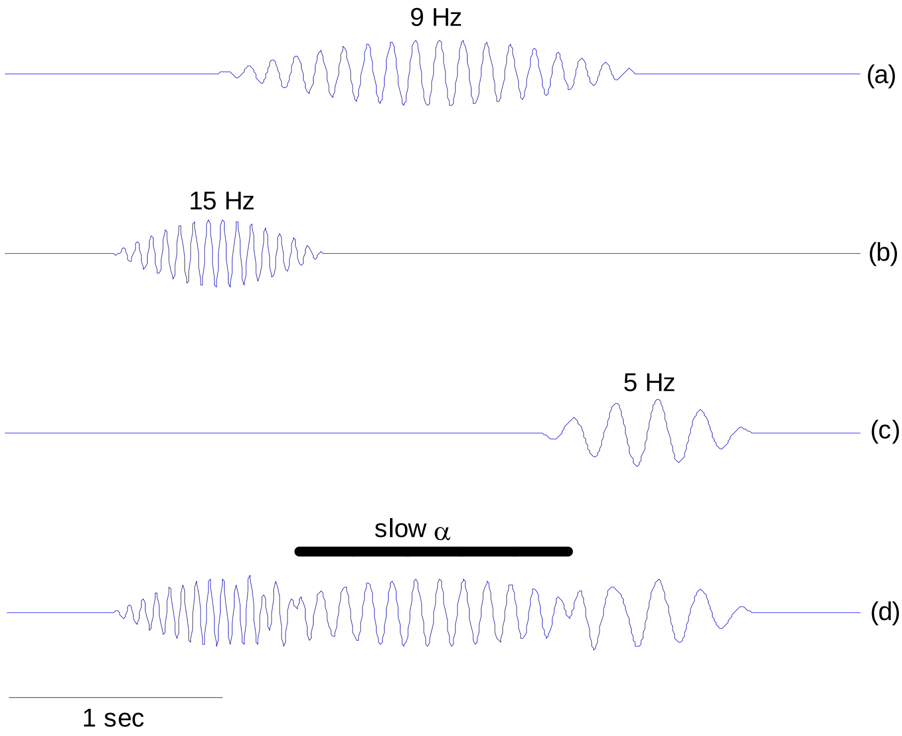


Figure 11 Slow-α detection from the time-varying rhythmic activities. The signal in (d) is simulated by adding three short-duration, amplitude-modulated sinusoids with frequencies (a) 9Hz, (b) 15 Hz, and (c) 5 Hz.

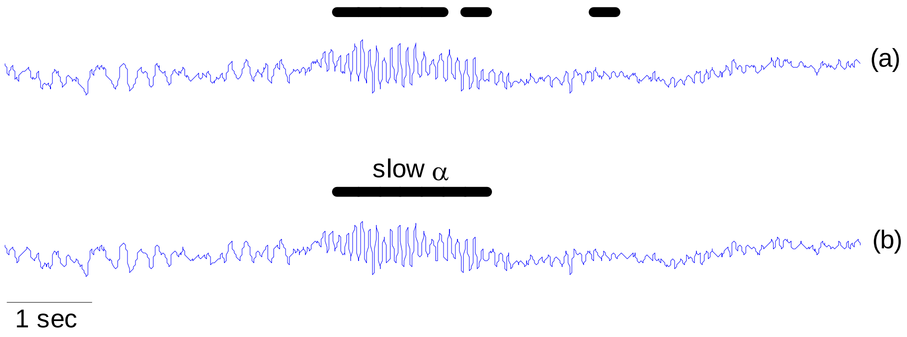


Figure 12 Detection of slow-α activity in meditation EEG.

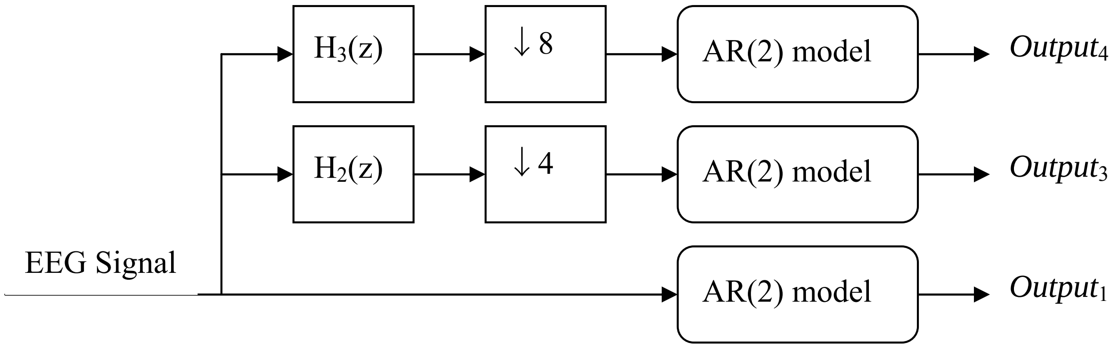
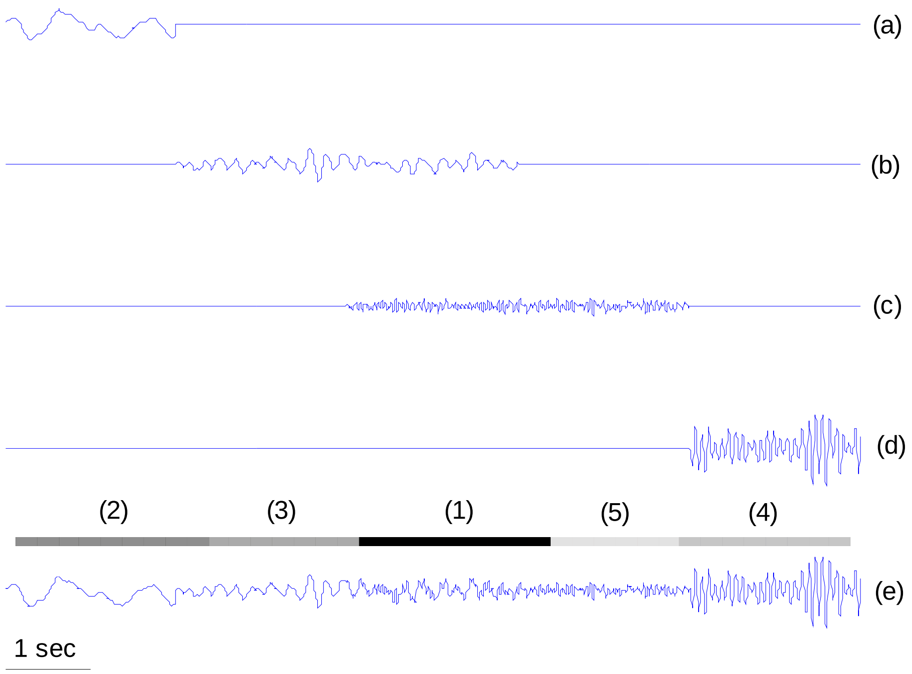


Figure 13 The *Subband-AR-EEG Viewer* modified for meditation EEG interpretation.



(1) χ, (2) Δ, (3) θ, (4) α, and (5) β.

Figure 14 Simulation results (a) △ activity (b) θ activity (c) β activity (d) α activity (f) simulated signal and classification results.

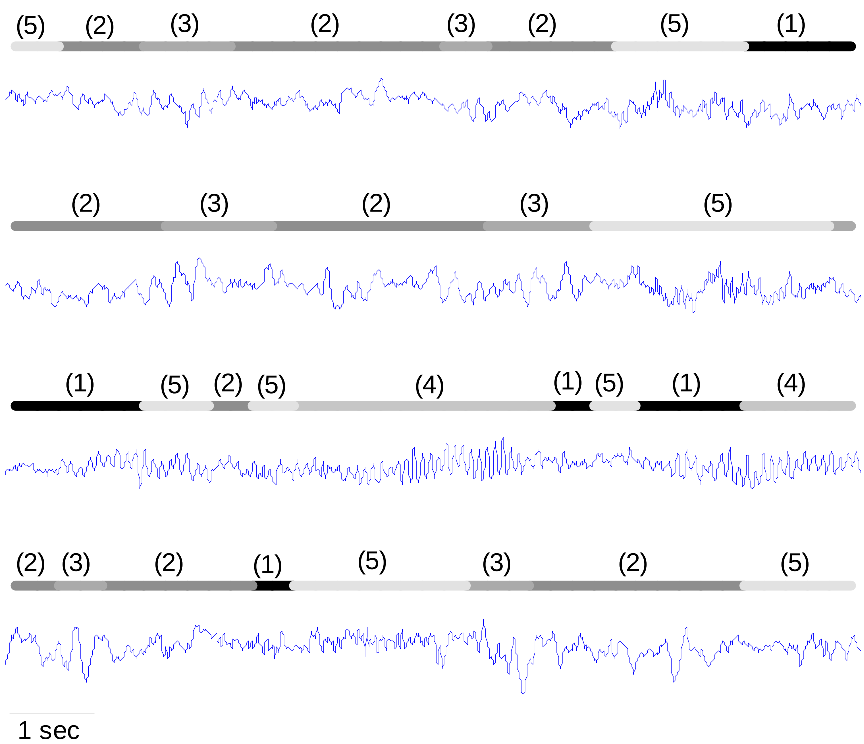
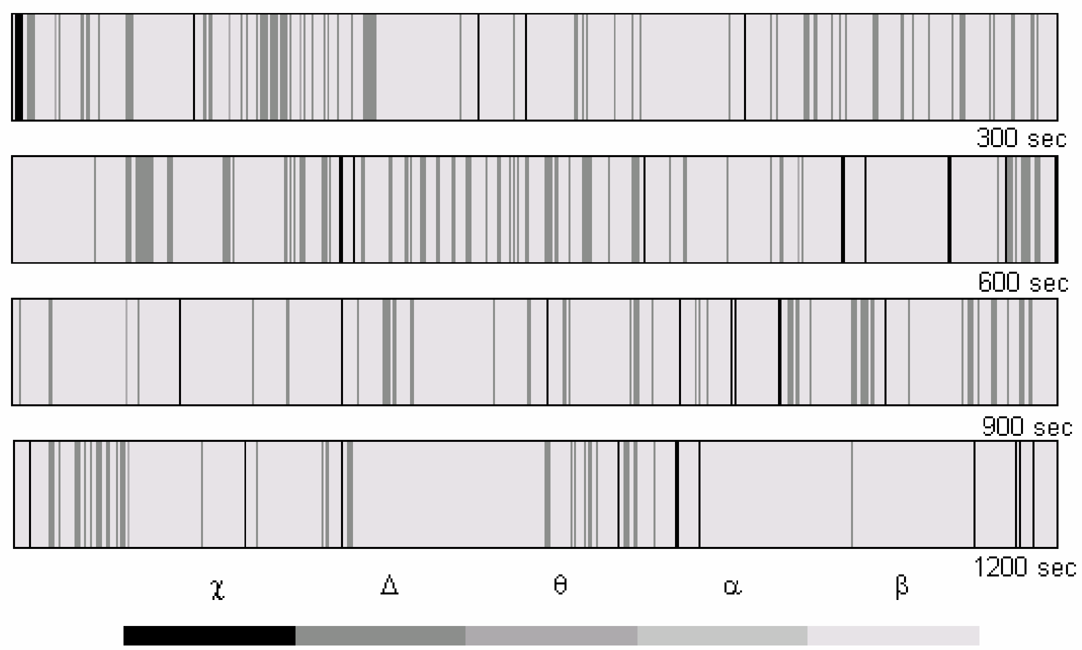


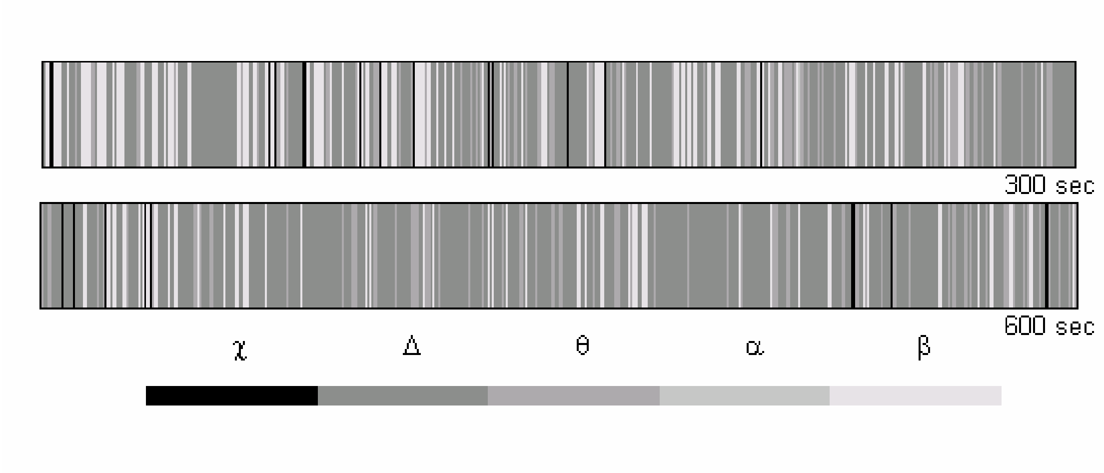
Figure 15 *Subband-AR-EEG Viewer* applied to the EEG signal for feature recognition.


300 sec
600 sec
900 sec
1200 sec
χ
Δ
θ
α
β

(a)

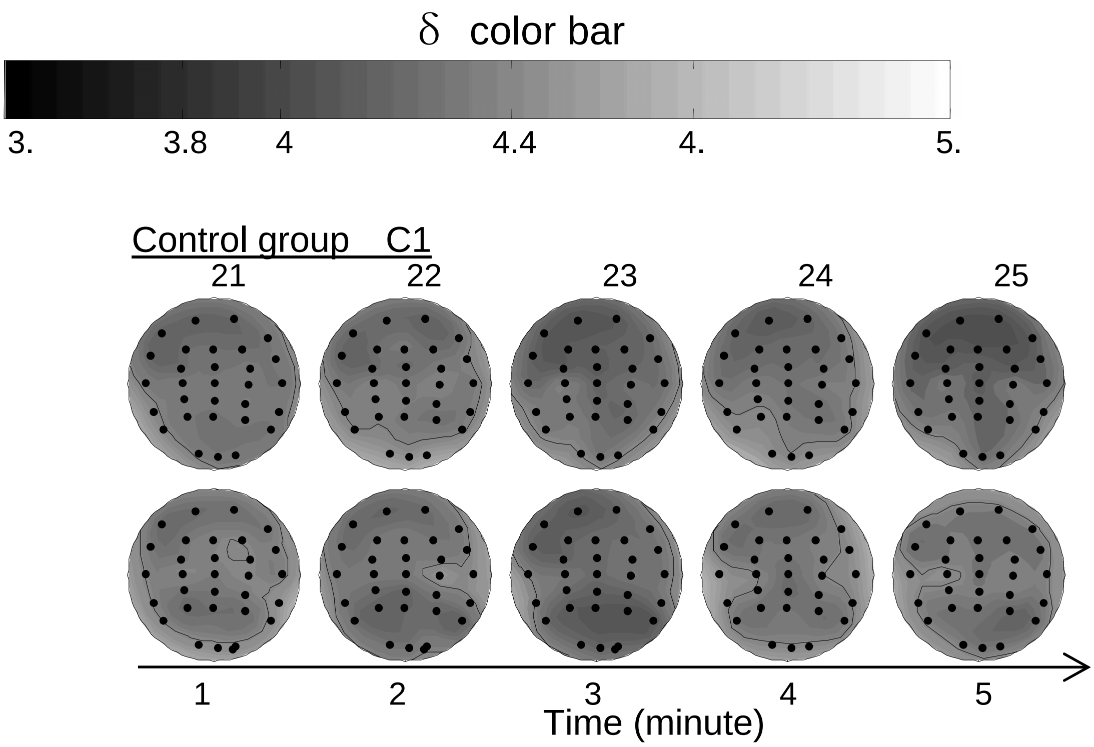

300 sec
600 sec
900 sec
1200 sec
χ
Δ
θ
α
β

(b)



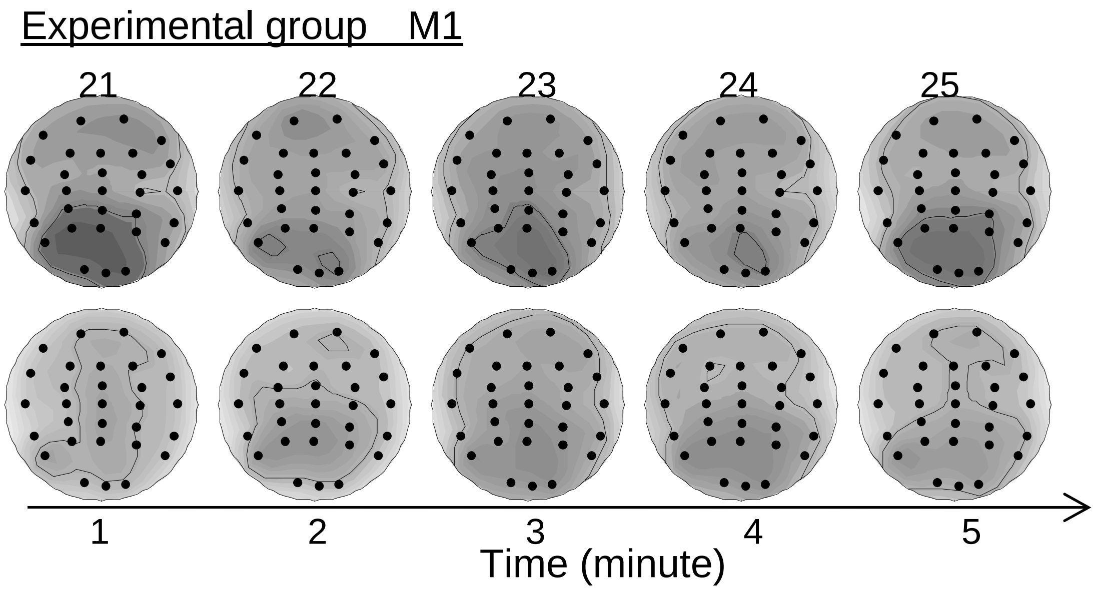
(c)

Figure 16 Running gray-scale charts for two meditators (a) 2k1019p, (b) 2k0830a, and one non-meditator (c) 2k1007p.

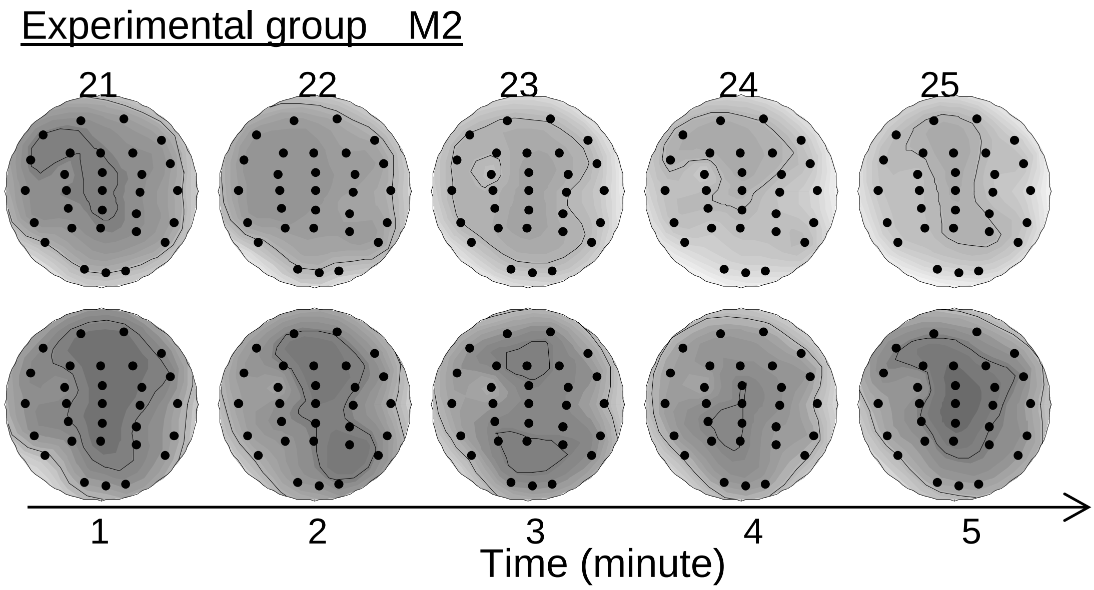


(a)

Figure 17 The brain mappings of $\bar{\delta}$ averaged over one minute for the control group (a) C1 and the experimental groups M1, M2, and M3 ((b)-(d)). The $\bar{\delta}$ mappings for the first and the last five minutes are shown, respectively, at the bottom and the top.

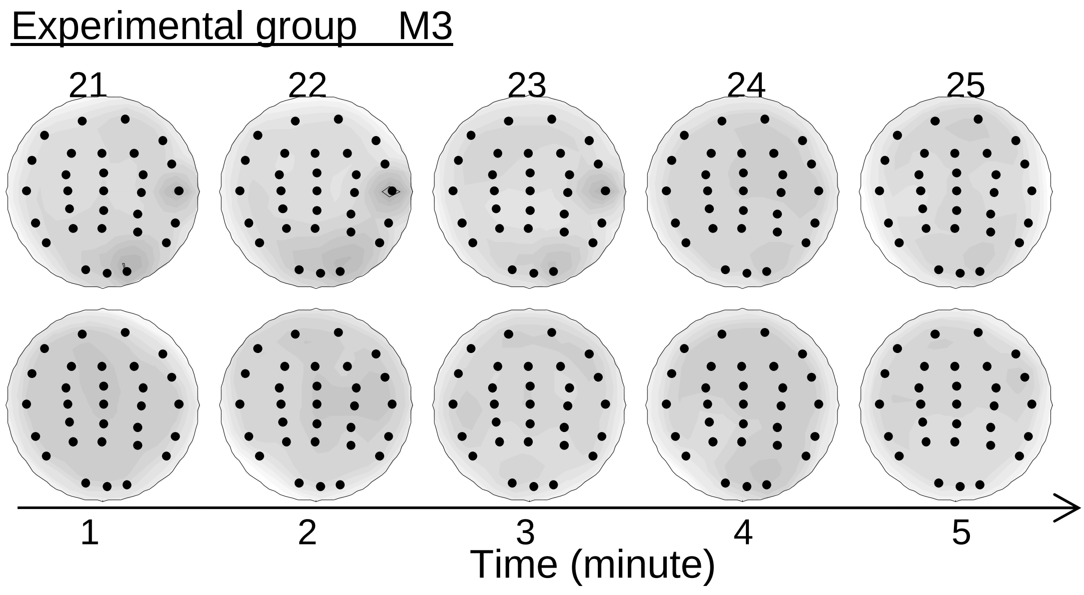


(b)



(c)

Figure 17 (continue).



(d)

Figure 17 (continue).

VIIII. SELF EVALUATION

In this three-year research project, we have attained to almost 90% of our aim proposed in the research plan: 1) compare the EEG of the meditators (experimental group and non-meditators (control group), 2) study the EEG evolution during the Zen-meditation process, and 3) establish the systematic database for quantitative results of analyzing the meditation EEG characteristics. In addition, we began to investigate the effect of Zen meditation on the flashed-light VEP (visual evoked potential), ECG (electrocardiograph), BPW (blood-pressure wave) about two years ago although the results are not included in this report. A large amount of valuable electrophysiological signals and data have been collected. Different methods and algorithms are being developed to intensively analyze the data in order to explore the inherent mechanism of health improvement through Zen-meditation practice.

Publications under the NSC support of this research funding include:

[1] Lo, P.-C. and Huang, H.-Y. (2004). Investigation of Meditation Scenario by Quantifying the Complexity Index of EEG, submitted to *Nonlinear Dynamics, Psychology, and Life Sciences*.

[2] Chang, K.-M. and Lo, P.-C. (2004). A survey of the Physical and Spiritual Health of Zen-Buddhist Practitioners, submitted to the *Journal of Alternative & Complementary Medicine*.

[3] Liao, H.-C. and Lo, P.-C. (2004). Meditation EEG Overview Based on Subband Features Quantified by AR Model, submitted to the journal of *Medical & Biological Engineering & Computing*.

[4] Chang, K.-M. and Lo, P.-C. (2003). Meditation EEG Interpretation Based on Novel Fuzzy-Merging Strategies and Wavelet Features, submitted to *Computers in Biology and*

Medicine, currently under revision.

[5] Lo, P.-C., Huang, M.-L., and Chang., K.-M. (2003). EEG alpha blocking correlated with perception of inner light during Zen meditation**.** American Journal of Chinese Medicine, 31(4):629-642.

(Conference papers are not listed here.)

Our work (Lo, Huang, Chang, 2003) has aroused the attention of many international research groups. We have received a number of requests for reprints from the U.S., the Europe, the Russia, etc.