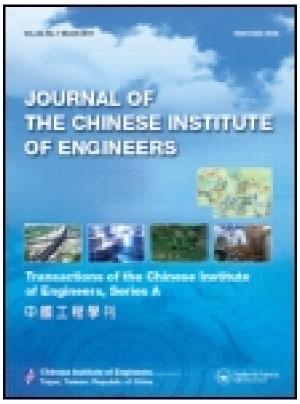

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Investigation of meditation scenario by quantifying the complexity index of EEG

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INVESTIGATION OF MEDITATION SCENARIO BY QUANTIFYING THE COMPLEXITY INDEX OF EEG

Pei-Chen Lo* and Hsuan-Yung Huang

ABSTRACT

A practitioner in true meditation should already transcend the physiological, mental, subconscious, and Alaya state, and eventually attain the spiritual realm. The scientific approach to the scope of Zen meditation provides insight into the mechanism in addition to the vague sketch of meditation sensation and its multiform benefits to human beings.

In meditation research, it is difficult to access changes of the consciousness state during meditation. Meditators once transcending the physiological and mental state cannot convey information outside. As a consequence, quantitative results together with post-experimental, subjective narration may provide us with a glimpse of the meditation scenario. This paper mainly reports our preliminary results of quantifying the long-term brain waves, recorded by the electroencephalogram (EEG), for both experimental (meditators) and control groups. Based on the nonlinear dynamic analysis of multi-channel EEG signals, we found that brain dynamics exhibited high $\overline{\delta}$ (Φ/β EEG) in deep meditation. Three different meditation scenarios have been identified from the running $\overline{\delta}$ (averaged complexity index) chart. Spatial characteristics also deviate from that of the control group. This observation was summarized from the results of analyzing the meditation EEG's collected from 17 Zen-Buddhist practitioners and 16 control subjects.

Key Words: meditation EEG (electroencephalogram), nonlinear dynamic theory, complexity, states of consciousness.

I. INTRODUCTION

For decades, the electrical activity of the human brain (electroencephalogram, EEG) has been extensively studied in order to help clinicians diagnose and treat brain disfunctions. As normally characterized by frequency, the EEG patterns are conveniently classified into four frequency ranges: the delta (Δ, $f < 4$ Hz), theta (θ, 4 Hz $\leq f <$ 8 Hz), alpha (α, 8 Hz $\leq f \leq$ 13 Hz), and beta (β, $f >$ 13 Hz). The role of the EEG in monitoring the nervous system has been explored with regard to normal and pathological conditions. The temporal and spatial features provide an access to the detection of focal EEG phenomena and to the exploration of regional function mapping (Kalayci and Özdamar, 1995). In addition to the popular time-domain and frequency-domain approaches, other techniques have been introduced and have proved useful in EEG analysis (van Gils *et al*., 1997). Among many other techniques, methods based on the nonlinear dynamic theory have been used to quantify underlying brain dynamics and evaluate EEG spatio-temporal complexity since more than one decade ago (Babloyantz and Destexhe, 1986; Lo and Principe, 1989; Rapp *et al*., 1989; Pijn *et al*., 1991). Furthermore, increased insight into brain dynamics revealed by EEGs contributes to computer-aided strategies for EEG interpretation (van Putten, 2001). A number of studies have reported the fruitful results of characterizing the dynamic behavior of the CNS (central nervous system) under various physiological or mental states (Kalayci and Özdamar, 1995; van Gils *et al*., 1997; Babloyantz and Destexhe,

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1986; Lo and Principe, 1989; Rapp *et al.*, 1989; Pijn *et al.*, 1991; Yaylali *et al.*, 1996; Destexhe *et al.*, 1988; Dvorak, 1990; Wackermann *et al.*, 1993; Aftanas, and Golocheikine, 2002). Despite the active discussion of CNS dynamics in the past decades, little is known about the electrophysiological characteristics of the CNS under a particular state of consciousness – Zen meditation.

The meditation EEG, although it has been investigated since the 1960s, is still an open question (Anand *et al.*, 1961; Kasamatsu and Hirai, 1966; Wallace, 1970; Banquet, 1973; Williams and West, 1975; Woolfolk, 1975; Pagano *et al.*, 1976; Elson *et al.*, 1977; Hebert and Lehmann, 1977; Bennett and Trinder, 1977; Corby *et al.*, 1978; West, 1980; Becker and Shapiro, 1981; Stigsby *et al.*, 1981; Heide, 1986; Jevning *et al.*, 1992; Istratov *et al.*, 1996; Travis, 2001). In the course of meditation, meditators experience various states of consciousness. According to their subjective narration, their mentality transcends the physiological (the fifth), mental (the sixth), subconscious (the seventh), and Alaya (the eighth) conscious state. How to characterize these states of consciousness based on a scientific approach becomes a matter of significance in understanding the meditation scenario. Notice that the effort to quantify sleep stages by EEG activities in the mid twentieth century has nourished the field of sleep study and further helped understand sleep problems, like insomnia. Up to the present, little has yet been disclosed regarding the phenomena of Zen meditation. Our group started with the exploration of Zen meditation based on the evolution of brain electrical activities, as shown by meditation EEGs. Scientific exploration of the meditation EEG may provide a contradistinction to the pathological EEG since a number of studies have corroborated the effectiveness of meditation practice on health promotion, hormone-level regulation, and the reduction of stress, anxiety, depression, etc. (Yu *et al.*, 2003; Newell and Sanson-Fisher, 2000; Coker, 1999; MacLean *et al.*, 1997; Tooley *et al.*, 2000; Lester, 1999; Shapiro *et al.*, 1999; Aftanas, and Golocheikine, 2001; Travis, and Pearson, 2000). Prayer and meditation have been used as health-enhancing techniques for centuries. There is growing attention to the health benefits of meditation. Consequently, biomedical research has continued to provide substantial evidence. Characterization of the EEG activities in different meditation states may help explore neuronal network and CNS properties involved in such "beyond-consciousness" states. One important goal is to assess the nature of the system's dynamics and its distinctive changes when brain waves make transitions between several states during the meditating process.

Three years ago, our research group started investigating the physiological characteristics of meditation, mainly focusing on the EEG (electroencephalograph) signals, of orthodox Zen-Buddhist practitioners (Lo *et al.*, 2003). A number of papers have reported the EEG findings of subjects practicing various meditation techniques (Anand *et al.*, 1961; Kasamatsu and Hirai, 1966; Wallace, 1970; Banquet, 1973; Williams and West, 1975; Woolfolk, 1975; Pagano *et al.*, 1976; Elson, 1977; Hebert and Lehmann, 1977; Bennett and Trinder, 1977; Corby *et al.*, 1978; West, 1980; Becker and Shapiro, 1981; Stigsby *et al.*, 1981; Heide, 1986; Jevning, 1992; Istratov *et al.*, 1996; Arambula *et al.*, 2001). Nonetheless, very few addressed understanding long-time meditating EEG records and their correlation with different consciousness states. We thus conducted a series of studies on meditation EEGs to explore the brain dynamics in the process. To reliably estimate the CNS dynamic parameters, intensive work is normally required for obtaining appropriate implementing parameters. It is not feasible for long-term monitoring. Alternatively, we evaluate the global dimensionality (Lo and Chung, 2000, 2001) that may reflect how the brain dynamics switches between various states of consciousness provided that the major aim is not to obtain exact values for dynamic parameters. This paper thus attempts to bring forth the time evolution schema of the meditating EEG based on changes in the CNS dynamic characteristics.

Although dynamic analysis furnishes important information about the CNS characteristics, tools from nonlinear dynamical theory used for EEG analysis, such as dimensional computation and Lyapunov exponent estimation, mostly suffer from the problems of indirect estimation, computational inefficiency and bias from implementing parameters (Lo and Principe, 1989; Yaylali, 1996; Lo and Chung, 2000). Thus they are not feasible for long-term schematic illustration of the meditation EEG. To deal with the problems, we introduced the method of estimating intrinsic dimensionality into multi-channel EEG analysis (Lo and Chung, 2000). Dimensional estimation actually offers a more reliable result in quantifying the brain dynamics than the method of estimating a Lyapunov exponent that is sensitive to the implementing parameters. Since dimensionality in a sense characterizes the global waveform complexity, we name it the "complexity index (δ)". Evaluation of complexity index is conceptually comprehensible and easily implemented based on local approaches (Fukunaga and Olsen, 1971; Pettis *et al.*, 1979; Verveer and Duin, 1995; Bruske and Sommer, 1998). Among the local approaches, the K's nearest neighborhood (KNN) analysis (Fukunaga and Flick, 1984; Passamante and Farrell, 1991; Michel and Flandrin, 1993; Trunk, 1976) provides an approach for directly estimating the δ, yet, with a drawback of spending an enormous amount of time on an exhausting search for the KNN distance. To solve the problem, we developed an efficient algorithm (Lo and Chung, 2001) that did not require computing all the inter-point distances and avoided the exhaustive sorting process. We also demonstrated that the computational time was significantly reduced, especially for a large number of data points (N) and recording channels (n). The algorithm is briefly illustrated in the following section. In section III, we intend to profile the meditation EEG based on the complexity-index analysis (δ analysis). The characteristic meditation EEG patterns will be presented with their corresponding trajectories and estimated δ's. Section IV examines some cases, including both the experimental and control groups, and explores various results of the running δ analysis.

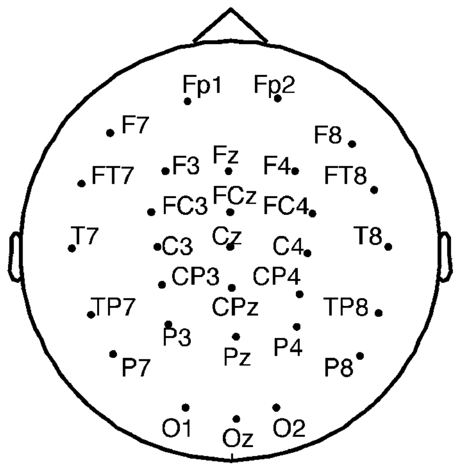

Fig. 1 The 30-channel recording montage

II. MATERIAL AND METHODS

1. Subjects and Data Collection

The EEG signals were collected from 17 Zen-Buddhist practitioners and 16 control subjects. Seventeen meditators (11 males and 6 females), average age 29.5 years, had been practicing Zen-Buddhist meditation for an average of 6.7 years (range 2 to 12 years). Sixteen control subjects(11 males and 5 females), average age 27.3 years, had no experience of any forms of meditation at all. All are healthy, and none reported accidents or illnesses that might affect their EEG patterns.

The EEG signals were recorded by a 30-channel electrode array with a common linked-mastoid (MS1-MS2) reference according to the international 10-20 method. Fig. 1 displays the recording montage. The signals were sampled at 200 Hz and filtered at 0.3-40 Hz. Experimental subjects were asked to meditate for 30 minutes. Controls were asked to sit and rest quietly with their eyes closed for the same period without falling asleep. After manually removing the artifacts such as eye blinking, eyeball movement and muscle activities by naked-eye diagnosis, nonlinear EEG analysis was performed on the 25-minute EEG segment free of artifacts.

2. Methods and Algorithms

Let $\boldsymbol{X} = \{\boldsymbol{X}_i\}_{i=1}^{N}$ 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 and 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) $\{x[i],\ i = 1, \cdots, N + (n-1)\tau\}$ to the phase-space trajectory $\boldsymbol{X} = \{\boldsymbol{X}_i = (x[i], x[i+\tau], \cdots, x[i + (n-1)\tau])\}_{i=1}^{N}$ preserves some topological invariants of the original system. Here τ represents the time delay in number of samples, and N is the number of vectors in the phase-space.

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

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

where the operator $\|\cdot\|$ evaluates the Euclidean distance. It was reported (Fukunaga and Flick, 1984; Lo and 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 $\boldsymbol{X}$. Thus, we proposed quantifying the global waveform complexity of multi-channel EEG by estimating the complexity index δ as follows (Lo and 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 $i = 1, \cdots, N$. 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 $\bar{\delta}$.

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 exhaustive sorting process (Lo and Chung, 2001). The approach mainly adopted the eigenfunction and principal-axis analysis. Let $[\boldsymbol{X}]$ 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 $[\boldsymbol{X}]$ is denoted by $[\boldsymbol{\Phi}]$, a $1 \times n$ row matrix. And $||\Phi|| = 1$. Then the transformation $[\boldsymbol{Y}] = [\boldsymbol{X}][\boldsymbol{\Phi}]^T$ results in an $N \times 1$ column matrix containing N scalars y_i, $i = 1, \cdots, N$ on the principal axis (the largest eigenvector). As a result, the inter-point distances of $\boldsymbol{X}_i$: d_{ij}, $j = 1, \cdots, N$ are mapped to

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

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

III. MEDITATING EEG FEATURES

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. Japanese Zen (Hentschel and Procaccia, 1983) was promulgated from mainland China where orthodox Zen Buddhism was first preached by Bodhidharma in 527 AC. Appendix A briefly introduces the religious background of orthodox Zen Buddhism. This is the first attempt to investigate the EEG phenomena, for this particular group, in the course of Zen-Buddhist meditation. 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). Fig. 2 illustrates the locations of these Chakras (refer to *Introduction of Zen Meditation*, lectured by Master Wu Chueh Miao Tien, published by Zen Cosmos, 2004). Gradually, the human life system enters a unique status in harmony with nature and the universe (called "the unification of heaven, earth, and human"). In the past decade, Zen-Buddhist meditation, as an unconventional

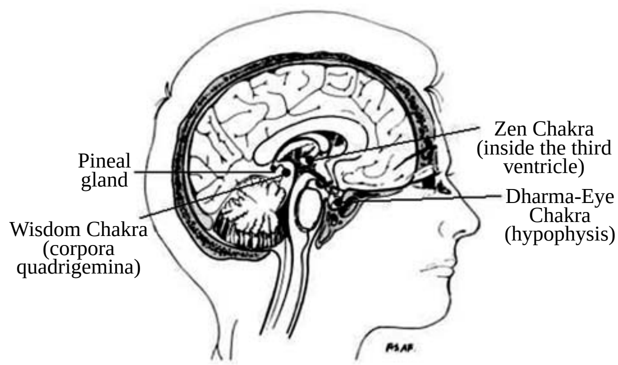

Fig. 2 Locations of the Zen Chakra, Dharma-Eye Chakra, and Wisdom Chakra

therapy, has proved efficacious for many chronic diseases (MacLean *et al*., 1997; Shapiro *et al*., 1999; Schneider *et al*., 1998), infections (Lo *et al*., 2003), and even some malignant tumors (Yu *et al*., 2003; Newell and Sanson-Fisher, 2000; Coker, 1999). Consequently, more people began to practice the Zen-Buddhist meditation in Taiwan. It aroused our attention to launch EEG investigation of Zen-Buddhist disciples. New findings have been continuously observed and reported (Lo *et al*., 2003).

The meditation EEG records collected from Zen-Buddhist disciples exhibit some characteristic features that have been constantly observed. Fig. 3 profiles those features from 5 meditators who demonstrate certain patterns frequently. In Fig. 3(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 characterized 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 state. The slow α (4th tracing) relates to the mind-concentrating status of the sixth conscious state. West reported finding slower α (8 ~ 10 Hz) with larger amplitude in the beginning of meditation (West, 1980). In Zen-Buddhist practice, meditators normally concentrate their mind on particular Chakra(s) in the beginning to release themselves from the flight of the imagination. We found that the EEGs 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 subjective narration by meditators, they may feel drowsy or enter the seventh consciousness (sub-consciousness). In Fig. 3(b), the 2D (two-dimensional) phase trajectories are constructed from the EEG epochs in Fig. 3(a) using a delay of 5 samples (0.025 second). Apparently,

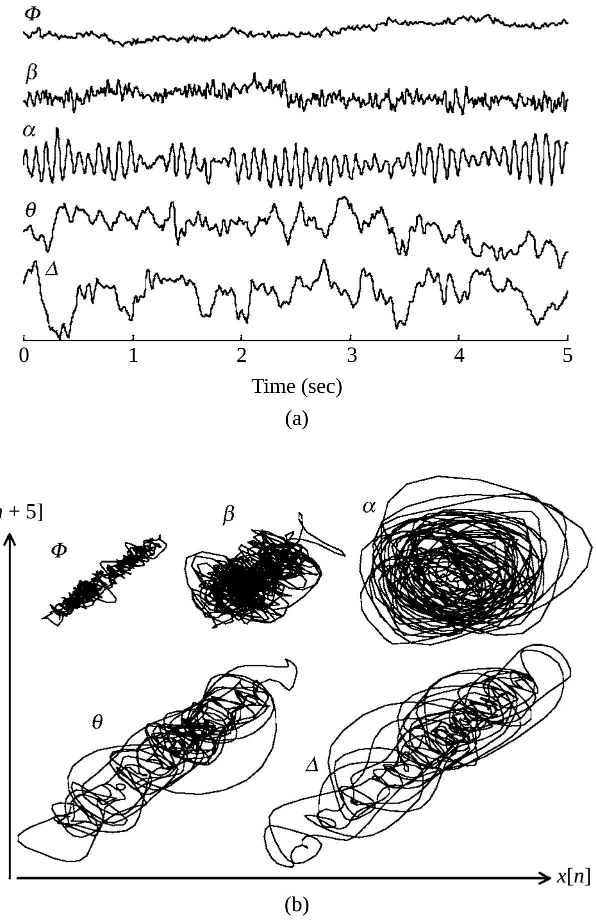

Fig. 3 Characteristic features constantly observed in meditation EEG: (a) the signals, (b) the 2D phase trajectories.

the silent and β patterns have phase trajectories of shrinking dynamic extent, yet with higher degrees 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 Fig. 3(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. Fig. 4 illustrates the dependence of complexity index δ on K for three Δ trajectories. Two

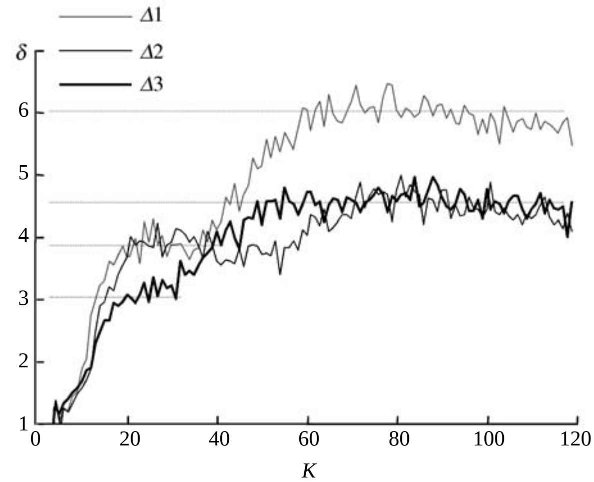

Fig. 4 The dependence of δ on values of K when analyzing the complexity index of the Δ rhythmic activity

distinct platforms appear on each curve, reflecting the multi-modal nonlinear mechanism. The lower platforms (K below 40) tend to characterize the Δ trajectories; while the higher platforms ($K > 60$) characterize the mix-modal nonlinear dynamics since computing the KNN distances often involves pairs of orbits corresponding to different EEG rhythms. As a consequence, the δ estimated is much higher. To determine the appropriate range of K's, it follows that a small K actually emphasizes the effects of superimposed noise while a large K causes the measurement involving multi-modal effects. Since the phenomenon of multi-modal effect is not evident for normal α, β and Φ rhythms, $\overline{\delta}$ computation is rather insensitive to a wide range of K. Accordingly, reliable estimates of $\overline{\delta}$ can be obtained with K ranging from 20 to 35 that are feasible for characterizing different EEG patterns.

At the current stage, the profiled meditation EEG patterns can be effectively differentiated into three groups based on the complexity-index analysis. The first issue encountered is the selection of implementing parameters. There is no analytical way to determine optimal parameters. Empirically based selection of time delay τ and embedding dimension n provides satisfactory results for interpreting meditation stages. In order to track potentially rapid changes in complexity, the analysis is performed over a short window length of 5 sec ($N = 1000$). Embedding dimension is chosen to be 6 since, for n above 6, the tendency of complexity index remains unchanged and the results of EEG analysis do not present significant changes. Time delay τ is determined by the first minimum of the autocorrelation function of EEG (Elbert *et al.*, 1994). The parameters applied in this study are: dimension $n = 6$, time delay $\tau = 5$ samples (0.025 second), and length $N = 1000$ samples (5 seconds).

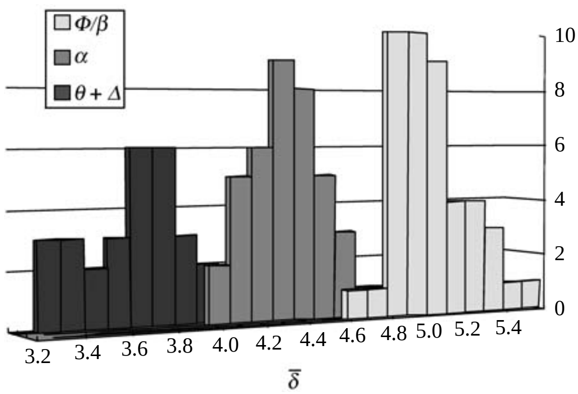

Fig. 5 Distribution of $\bar{\delta}$'s estimated for different characteristic EEG patterns during meditation

Table 1 Distribution of complexity index ($\bar{\delta}$) of characteristic EEG features collected from 17 meditators; implementing parameters applied: n = 6, τ = 5 samples, epoch length: 5 seconds (100 samples), 20 ≤ K ≤ 35

	Mean of $\bar{\delta}$	Std of $\bar{\delta}$	Number of epochs analyzed
I: $\theta + \Delta$	3.611	0.200	28
II: α	4.287	0.186	40
III: Φ/β	4.932	0.193	44

The final estimate, $\bar{\delta}$, is obtained by averaging the δ's derived with K ranging from 20 to 35. As shown in Fig. 5 and Table 1, the complexity index of group I is 3.61 ± 0.20, estimated from a bin of 28 sampled epochs comprising the slow and large-amplitude rhythmic patterns. They are mostly the θ and Δ patterns which occurred intermittently in the midst of meditation. EEG patterns of this group are thus denoted by '$\theta + \Delta$'. Impurity of the rhythmic patterns in this group causes the scattered estimates. The complexity index of group II, involving 40 α-rhythm epochs, is estimated to be 4.29 ± 0.19. Group III contains the patterns of great interest in our meditation EEG study. Complexity-index analysis fails to discriminate between the β and the "silent" (Φ) patterns. Group III is accordingly denoted by 'Φ/β'. Both are highly correlated with the serene, "beyond-consciousness" brain dynamics according to our investigation. The largest $\bar{\delta}$ (4.93 ± 0.19) is obtained from this group. It should be noted that each meditator has his/her particular symphony of meditation EEG patterns. Not every pattern appears in the meditation course. We thus explore the meditation EEG schema in the next section, mainly focusing on the proportion of Φ/β activity.

IV. MEDITATION EEG SCHEMA

This section discusses long-term evolution of CNS dynamics, based on running $\bar{\delta}$'s, under various states of consciousness during meditation. As the complexity index reflects the fractional dimension of CNS, it provides certain nonlinear measures that can be used to monitor the meditation process. Furthermore, increased insight into correlation between the "consciousness" states and the nonlinear quantitative indexes may provide access to both the meditation depth and the meditation scenario. In the meditation research study, it is difficult to access changes of the consciousness state during meditation. Meditators once transcending the physiological and mental state cannot signal the operator. One reason is that the experimental subjects frequently forget. In other words, meditators cannot attain the optimal meditation if they are obligated to follow the experimental protocol. As a consequence, quantitative results together with the post-experiment interview may provide us with a glimpse of the meditation scenario.

Fluctuation of $\bar{\delta}$ reflects time evolution of the CNS nonlinear mechanisms generating the meditation EEG activities profiled in the previous section. We have shown that the running $\bar{\delta}$ curve was able to identify the occurrence of EEG focal-sharp-wave events and quantify the EEG spatial correlation for epileptic seizures (Lo and Chung, 2000 pp. 910-913). Apparently, more complication is involved in monitoring the meditation EEG since a number of characteristic EEG patterns are expected to occur during the meditating course. As addressed in the previous section, three distinct groups of EEG phase trajectories are discernible in consideration of characterizing the meditating EEG patterns based on the estimated $\bar{\delta}$. In consideration of providing an overview of meditation EEG records, feature coding and illustration schemes require the selection of thresholds. The thresholds are subject-dependent and insert additional bias into the interpretation. To prevent these drawbacks and reduce the sophisticated process following the $\bar{\delta}$ computation, the running $\bar{\delta}$ is directly displayed as a gray-scale chart by mapping the resulting range of $\bar{\delta}$, ($\bar{\delta}_{min}$, $\bar{\delta}_{max}$), into the gray-scale range, (0, 255).

The efficient algorithm proposed (Lo and Chung, 2001) is applied to several EEG records collected from both experimental and control groups (non-meditators). The running measurement uses a window length of N = 1000 (5 seconds) and a moving size of 100 points (0.5 second). We have reported previously (Lo, Huang, and Chang, 2003) our observation of a significant correlation between perception of the inner light (spiritual energy inside the third ventricle, the Zen

Table 2 Characteristics of EEGs and the range of more than 70% of $\bar{\delta}$ for the control group and three experimental groups

	O2 EEG characteristics	$\bar{\delta}$ range (1st 5 min)	$\bar{\delta}$ range (last 5 min)
C1	α dominates, (θ + Δ) emerges intermittently	4.0-4.8	4.0-4.8
M1	Transit from Φ/β to irregular, intermittent α or (θ + Δ)	> 4.8	4.45-4.8
M2	Transit from α dominating to Φ/β	4.0-4.8	> 4.8
M3	Φ/β dominates throughout the meditation course	> 4.8	> 4.8

Chakra shown in Fig. 2) and the alpha blocking in the occipital cortical region, after performing a few studies on different subjects. On the other hand, there are more noisy recordings appearing on the O1 channel according to our experience. We thus focus our investigation on channel-O2 EEG that reflects a meditating stage of particular interest in Zen-Buddhist meditation. According to the results of analyzing the meditation EEG's of 17 experimental subjects, we identified three different groups (M1, M2, and M3) of meditation EEG scenarios. Each group reflects a typical temporal evolution of brain electrical activities and states of consciousness. Details are illustrated below. Table 2 illustrates the characteristics of three experimental groups and one control group. Fig. 6 displays the 25-minute running $\bar{\delta}$ measures for the representatives in the control group (C1) and three experimental groups. Each long strip of gray-scale image traces the running $\bar{\delta}$'s for five minutes (approximately 600 $\bar{\delta}$'s). The "$\bar{\delta}$ color bar" shown on the top specifies the mapping of $\bar{\delta}$ range (3.5, 5.3) onto gray-scale range (0, 255). Brighter gray (lager $\bar{\delta}$) highly correlates with the occurrence of β rhythm or low-voltage activity (Φ/β). The α rhythm mostly results in mid-tone grays. As the EEG oscillates at a slower rate, often accompanied by increasing amplitude ($\theta + \Delta$), the gray becomes darkened. In the control group (non-meditators), a typical gray-scale chart of running $\bar{\delta}$ mostly contains a large portion of mid-tone grays (C1 section in Fig. 6). On the other hand, the meditation EEGs of experimental subjects reveal quite different characteristics. In our study of seventeen experienced Zen-Buddhist meditators, the meditation scenarios, based on the running $\bar{\delta}$ measures, can be categorized into three distinct groups: bright-to-mid/dark grays (M1), mid-to-bright grays (M2), and all-bright grays (M3). Meditators of group M1 reveal a meditation process beginning with Φ/β activities, transiting through irregular α or slow-rhythm ($\theta + \Delta$) intermittent stage, and settling at the rhythmic θ trains or α dominated activities after a twenty-minute meditation. Most subjects in group M1 did not achieve good-quality meditation due to drowsiness (which normally occurred at the sub-consciousness state) or

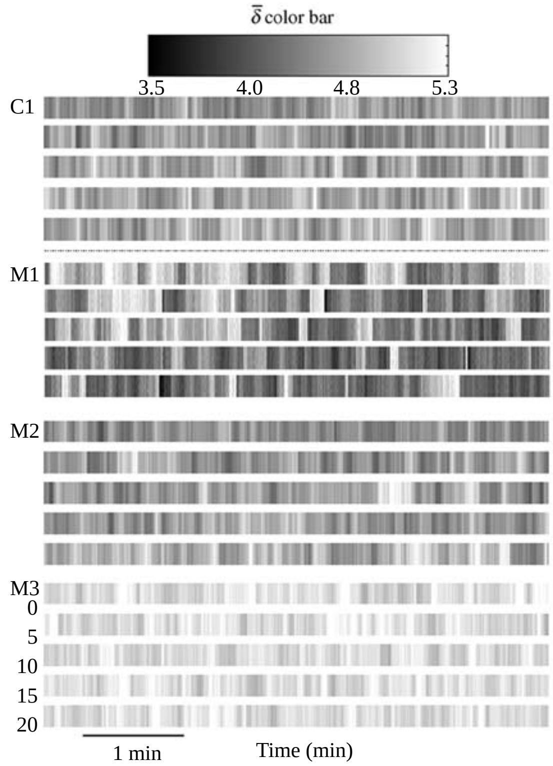

Fig. 6 The 25-minute running $\bar{\delta}$ charts (channel O2) for the representatives in the control group (C1) and experimental groups (M1, M2, and M3)

mental alertness. The meditation EEG of group M2 exhibits characteristics totally different from that of group M1. In the beginning meditation, α dominates the EEG, reflecting the brain state in relaxed, normal consciousness. As a meditating session continued, however, β-rhythm occurred or, alternatively, EEG power was significantly suppressed occasionally (group III: Φ/β in Fig. 5). A group-M2 meditator with seven-year meditation experience portrayed his meditation scenario as follows: "... as I felt the energy vibrating inside my body, I also perceived magnificent light, green, red, and purple light, that was beyond imagination, without doubt." Another one described the experience of entering a realm of totally peaceful and uniform mind after transcendence "... at which state I felt myself surrounded by sacred light." "Moreover, some kind of energy, or supernatural power drilled through my skull and rejuvenated my brain and body," added by the same person. And we find that most Zen-Buddhist disciples experience this kind of *supernaturalism*. Meditators in the third group (M3) reveal a common feature, Φ/β, throughout the meditation course. The low-amplitude EEG sometimes has its amplitude suppressed down to almost null. Or, large amounts of β-rhythms may emerge. They mostly experienced the transcendental, sacred aura with mind-body uniformity during the entire meditation course. A typical example was recorded from one meditator with ten-year meditation experience, who is also an artist specializing in Buddhist-statue art painting. He is one of a few disciples in this Zen-Buddhist group who often perceive the sacred Buddhist statue with their Dharma eye. This observation coincides with our previous report (Lo, Huang, and Chang, 2003).

In Fig. 7, we further present the running $\bar{\delta}$ chart analyzed for selected 8-channel EEGs, including channels F3, F4, C3, C4, P3, P4, O1, and O2 for the same representatives as in Fig. 6. We notice that the beginning five-minute EEGs are pretty much the same for the control subjects and the group-M2 meditators in the occipital brain region (Fig. 7(a)). 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 being limited to the occipital region. Nonetheless, group-M2 meditators exhibit lower complexity in brain dynamics corresponding to the slow ($\theta + \Delta$) 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 ($\theta + \Delta$) (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 in 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 spread all over the scalp. Brain dynamics of high dimension and high complexity might be referred to the *transcendental* state of consciousness. After a twenty-minute recording, the $\bar{\delta}$ charts differ a lot among the four groups (Fig. 7(b)). 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 an increasing proportion of α rhythms on the parietal and occipital regions. Group-M2 subjects enter into the high-complexity brain dynamics (Φ/β), as in 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. Via the practice, the human life system enters a unique status in harmony with nature and the universe. The meditators in group M3 are special. Their EEGs have been steady all the way through the meditation course. Particularly, α rhythm has never even appeared since the beginning of meditation. The meditators in this particular group said that their brain and mentality had become totally different from what they were before practicing Zen-Buddhist meditation. They are now very calm, serene and peaceful when they are not in use. This status makes the meditators better preserve their mental power and body energy.

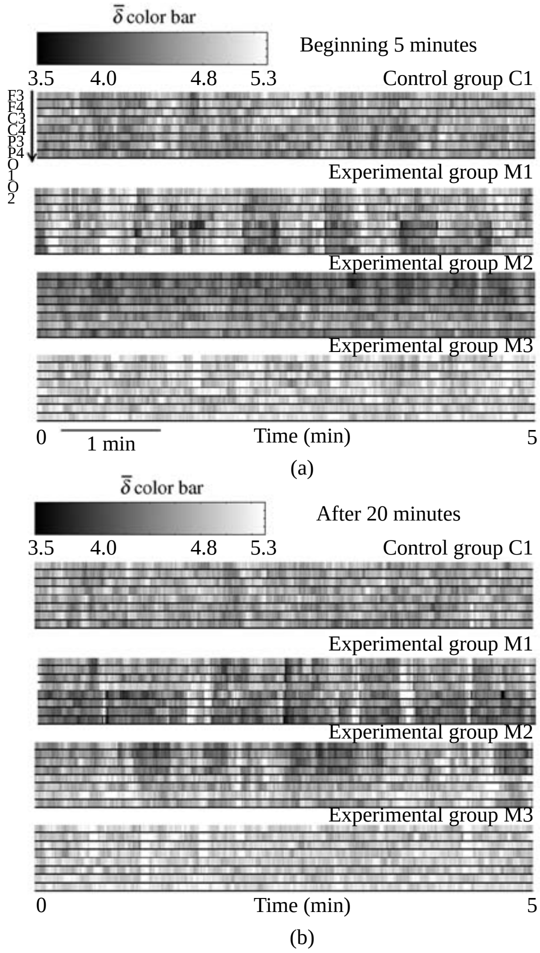

Fig. 7 The 8-channel running $\bar{\delta}$ charts for the representatives in the control group (C1) and experimental groups (M1, M2, and M3). (a) the beginning 5-minute $\bar{\delta}$ charts, (b) the 5-minute $\bar{\delta}$ charts after meditating for 20 minutes.

Note that the EEG involves both spatial and temporal information. The illustration in Fig. 7 above is able to present the detailed spatio-temporal variation, yet, with poor quality for investigating the spatial localization. The brain mappings of one-minute averaging $\overline{\delta}$ in Fig. 8, reconstructed from the 30-channel EEGs, correlate closely with the observations in Fig. 7. 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. DISCUSSION

This work is devoted to the investigation of physiological and mental characteristics of individuals having been practicing the Zen-Buddhist meditation for years. The significance of the work is hard to overemphasize, especially since meditation practice has been proven to benefit mankind, including health, character, life outlook, social morality, etc. In this paper, EEGs were 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. Based on the concept of fractional dimension estimation in nonlinear dynamic theory, running measurement of averaged complexity index ($\overline{\delta}$) has been developed and implemented to measure long-time meditation EEGs 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 $\overline{\delta}$ charts somehow correlate with the subjective illustration of their meditation sensation. However, a 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. To report, they must return 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 Zen-Buddhist meditation in 1999. Nevertheless, scientific curiosity may lead into the exploration of the myths of the spiritual realm.

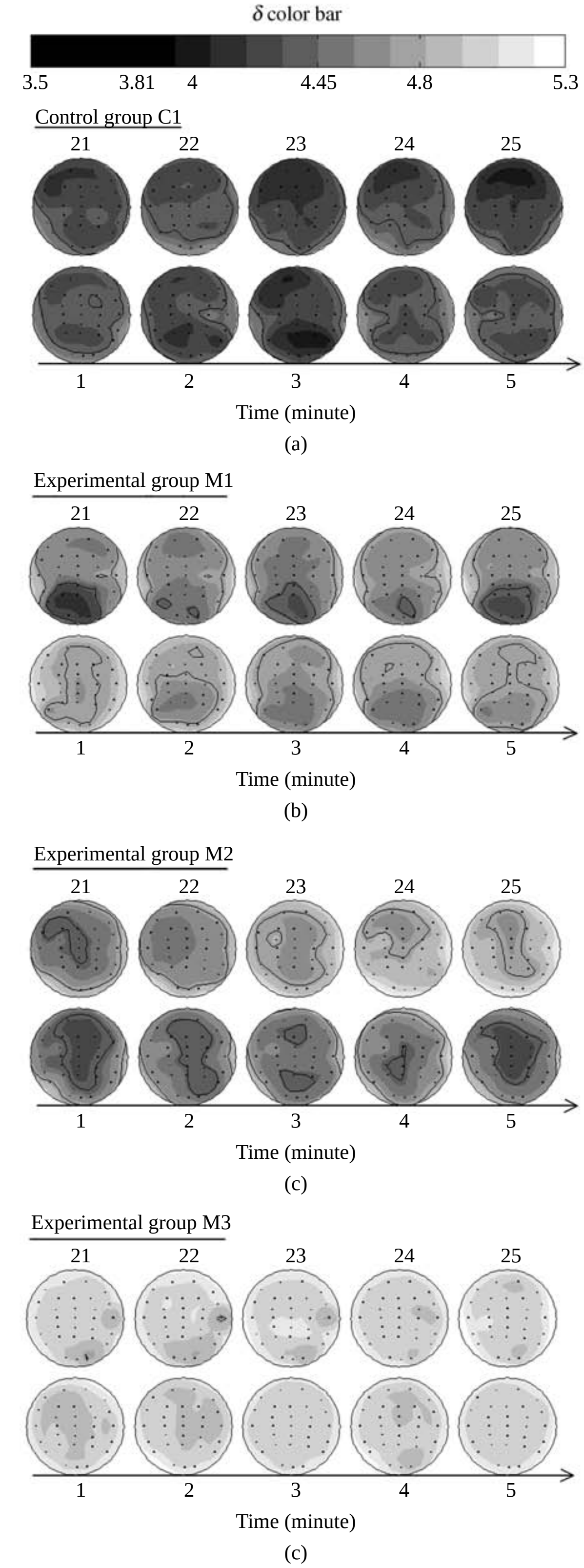

Fig. 8 The brain mappings of $\overline{\delta}$ averaged over one minute for the control group (a) C1 and the experimental groups M1, M2, and M3 ((b)-(d)). The $\overline{\delta}$ mappings for the first and the last five minutes are shown, respectively, at the bottom and the top.

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APPENDIX A

In the preaching history of Zen-Buddhism, Buddha Shakyamuni found the eternal truth, the supreme wisdom, the noumenal energy, and the natural powers of the universe in meditation under a linden tree. The orthodox Zen Buddhism originated when Buddha Shakyamuni transmitted this light of wisdom to the Great Kashiyapa some 2,500 years ago. The same path towards perfect enlightenment (Buddhahood) was promulgated in mainland China in 527 by Bodhidharma, the 28th patriarch. The current patriarch is Zen master Wu Chueh Miao Tien (or simply "Miao Tien"), the 85th patriarch of the orthodox Zen-Buddhism Sect since the Great Kashiyapa. In orthodox Zen-Buddhist practice, 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 promulgate the true message of Zen, which can only be preached by a master who has achieved the Buddhahood.