Synchronization Analysis of EEG Signals Evoked by Manual Acupuncture

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Abstract: Manual acupuncture (MA), as a mechanical action, can be equivalent to an external stimulus to the neural system. However, the regulation and action mechanism of acupuncture is still unclear. In the present study, synchronization levels of brain activities evoked by MA is investigated. We design an experiment that acupuncture at Zusanli with four different frequencies to obtain electroencephalograph (EEG) signals. Since neural system is a complex nonlinear dynamics system that possesses strong nonlinear characteristic, phase synchronization (PS) based on recurrence plot method is introduced to quantify the synchronization between EEG signals induced by MA. It is found that the synchronization between different brain regions during acupuncture is obviously lower than that before acupuncture, which can prove that MA has effect on the brain.

Key Words: Phase Synchronization, Acupuncture, EEG, Nonlinear

1 INTRODUCTION

Manual acupuncture, as an ancient therapeutic technique, has been gradually recognized by the world through over two thousand year clinical trails. However, the regulation and action mechanism of acupuncture is still unclear. Synchronization, which is a universal phenomenon in coupled nonlinear systems [1], plays an important role in the nervous system [2, 3]. Experimental evidences demonstrate that synchronous neuronal oscillations in neural networks is a major candidate mechanism for integrating and representing information in the brain [4–6], such as binding problem [7], selective attention [8], memory formation [9] and sleep [10, 11]. If large-scale synchrony is the basis for normal brain functioning, then synchrony disruption should cause functional abnormalities [12]. Recently, researches have discovered that many pathophysiological phenomena such as neural diseases are caused by abnormal synchronization or desynchronization of neural populations. Epileptic seizures, for example, are highly synchronous events [13–15]. In Parkinson’s disease, numerous experimental studies have demonstrated that neurons within both the STN and GPi show an increased level of synchrony during TREMOR states [16, 17]. It has also been proposed that a disruption of synchrony is related to the fragmented cognitive experience of patients with Schizophrenia [18, 19]. Therefore, synchronization is an important mechanism that helps us in understanding information processing in a normal or abnormal brain [20]. The estimated synchronization of the experimental and clinical data become the signatures of brain pathologies, or brain functions, or the early diagnosis and monitoring of brain disorder [21, 22]. Such synchronous oscillations arise when large groups of neurons fire in synchrony. These mechanisms can be studied at the macroscopic level with neurophysiological techniques such as the electroencephalograph (EEG), which can record multi-channel neural signals in different areas of the brain simultaneously with high time resolution.

Acupuncture, as an external stimulus, can induce the electrical activities of the neural system, thus influence the evolving process of information in the brain. Synchronization can represent cortical-cortical interactions during MA. Hence, we estimate the synchronization index of EEG signals evoked by MA to investigate the effect of MA on the neural system. Up to now, EEG has not been widely used to study the mechanism of MA yet.

Some methods have been developed to estimate the synchronization index between two neural series, for instance cross-correlation, spectrum-based coherence, synchronization likelihood, mutual information, nonlinear interdependence, phase synchronization, correntropy coefficient, event synchronization, GSI (genuine synchronization index) and RSI (random synchronization index), and so on.
Figure 1: Acupuncture experiment. (a) Electrodes position on the brain; (b) Acupuncture process. (c) EEG signals evoked by MA for one volunteer at six states.

There are three basic types of synchronization between two complex systems, i.e., completely synchronized, generalized synchronized, and phase synchronized. However, under experimental conditions it is difficult and mostly impossible to have completely synchronization. Hence, it is important to study a relative weak degree of synchronization, where the phases and frequencies of the chaotic oscillators become locked, whereas their amplitudes remain almost uncorrelated. This behavior is denoted by phase synchronization (PS). PS is essential for large-scale integration. The evidence is well grounded in single-cell recordings and LFPs studies in animals, and also EEG measurements in humans [6].

Since EEG signals reflect the function of neural network assemblies with nonlinear components, nonlinear analysis methods are capable of extracting more informative features from EEG signals. Therefore, in this paper, we employ PS based on recurrence plot to analyze the degree of synchronization of EEG signals evoked by different MA frequencies, i.e. 50, 100, 150 and 200 times/min. Each frequency acupuncture last for 2 minutes. Relax 10 minutes for the intervals.

EEG signals are recorded during the whole acupuncture experiment process with a sampling rate of 250 Hz according to the 10-20 International System, from 20 scalp electrodes, i.e. Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, OZ and O2, with two linked earlobe electrode reference (Figure 1(a)). The amplifier bandwidth is set between 0.1 and 100 Hz.

To investigate the effect of MA on synchronization between different brain scalp regions, we intercept 6 EEG epochs from EEG data of each volunteer, which are the representative sample of brain activity for six states of the experiments, i.e., before acupuncture, acupuncture with 50times/min, 100times/min, 150times/min, 200times/min and after acupuncture, respectively (Figure 1(c)). Each selected epoch lasts for 80s. In order to eliminate artifacts by residual EMG and noise, all selected epochs were digitally filtered with cut-off frequencies at 0.5-48Hz.

### 2.2 Phase Synchronization by means of recurrences plot

The concept of recurrence can be used to detect indirectly PS in a wide class of chaotic systems and even for time series corrupted by noise, where other methods fail [29]. For a given a time series \( \{x_i\}_{i=1}^{N} \), a recurrence plot (RP) can be obtained by the method proposed by Eckmann et al. [30] as follows.

\[
R_{i,j}(\varepsilon) = \Theta(\varepsilon - \|x_i - x_j\|), \quad i, j = 1, \ldots, N
\]

where \( x_i \) is the phase space vector, which can be reconstructed by using the Taken’s time delay method, \( x_i = [x_i, x_{i+\tau}, x_{i+2\tau}, \ldots, x_{i+(m-1)\tau}] \) \( m \) and \( \tau \) are the embedding dimension and the lag, which can be determined by
Cao method [31] and FNN method [32], and mutual information method [33], respectively.\(^{N} = n - (m - 1)\tau\) is the number of the phase space vectors; \(\varepsilon\) is a threshold distance; \(\Theta(\cdot)\) is the Heaviside function (i.e. \(\Theta(x) = 0\), if \(x < 0\), and \(\Theta(x) = 1\) otherwise).

In the RP, diagonal lines indicate the existence of some determinism in the system under consideration. The vertical distances between these diagonal lines reflect the characteristic time scales of the system. The distances between the diagonal lines are not constant, i.e. we find a distribution of distances, reflecting the different time scales present in the chaotic system.

If two oscillators are in PS, the distances between diagonal lines in their respective RPs coincide, because their phases, and hence their time scales adapt to each other. If the probability that the first oscillator recurs after \(\tau\) time steps is high, then the probability that the second oscillator recurs after the same time interval will be also high, and vice versa. Therefore, looking at the probability \(p(\varepsilon, \tau)\) that the system recurs to the -neighborhood of a former point \(x_i\) of the trajectory after \(\tau\) time steps and comparing \(p(\varepsilon, \tau)\) for both systems allows detecting and quantifying PS properly. \(p(\varepsilon, \tau)\) can be estimated directly as follows[34]

\[
\bar{p}(\varepsilon, \tau) = 1/(N - \tau) \sum_{i=1}^{N-\tau} R_{i,i+\tau}(\varepsilon) \tag{2}
\]

For two systems \(x\) and \(y\), PS can be quantified by the correlation coefficient between \(p_x(\varepsilon, \tau)\) and \(p_y(\varepsilon, \tau)\).

\[
CPR = \langle \bar{p}_x(\varepsilon, \tau) \bar{p}_y(\varepsilon, \tau) \rangle \tag{3}
\]

where \(\bar{p}_x(\varepsilon, \tau)\) and \(\bar{p}_y(\varepsilon, \tau)\) are the probabilities normalized to zero mean and standard deviation of one. If both systems are in PS, the probability of recurrence will be maximal at the same time and \(CPR \approx 1\). On the other hand, if the systems are not in PS, the maxima of the probability of recurrence will not occur simultaneously. Then a drift is observed and the values of \(CPR\) is low.

3 PS ANALYSIS OF EEG SIGNALS EVOKED BY ACUPUNCTURE

In order to investigate the effect of MA on the synchronization between different brain regions, the proposed method is applied to analyze a 20-channel scalp EEG signals evoked by MA. \(CPR\) of each pair channel of EEG signals at six states for all volunteers are estimated to investigate synchronization changes between different brain regions under different MA stimulus. \(CPR\) is calculated in 4s-length sliding windows with shifting step of 1s, producing \(CPR\) sequences. Then the average \(CPR\) value of all sliding windows can be obtained. For comparison between different volunteers, results of each volunteer at six states are normalized between 0 and 1. As a result, six 20 \(\times\) 20 matrices are obtained for every volunteers at six states, respectively.

Figure 2 shows the average synchronization between pairs of EEG channels for all volunteers at six states. (The values of corresponding elements in PS matrices obtained from 8 volunteers is turned into a matrix, which represents the average synchronization level for all the volunteers.) The different gray levels (colors) represent different \(CPR\) between two channels series. It is found that \(CPR\) during MA is obviously lower than that before MA, which means that MA weakens the synchronization between different brain regions. Figure 3 lists the synchronization conditions between different EEG channels for one of the volunteers, which shows the same re-
results as the whole obtained from Figure 2. Moreover, to test these observed mean differences statistically, the one-way ANOVA test is performed for CPR values at six states for all volunteers, as shown in Figure 4. The results suggest that CPR of EEG signals during acupuncture has significantly lower values than that before acupuncture at probability level P=0.05. The results above turn out that MA has effect on the degree of synchronization between different brain regions.

4 CONCLUSION

To study the effect of MA on the brain activity, we analyze the degree of synchronization of EEG signals evoked by MA at Zusanli acupoint from 8 volunteers at six states using CPR measures, which can quantify nonlinear synchronization interactions between different brain regions. The higher CPR suggest higher synchronization level. To our knowledge, this is the first paper to use CPR to analyze the EEG signals evoked by MA for understanding the effects of acupuncture on the brain activity. It is found that synchronization level of the brain during acupuncture is higher than that before acupuncture, which means that MA has the effect on the brain. The result can provide a theoretical support for uncovering the regulation and action mechanism of acupuncture.

REFERENCES


