Remote synchronization of brain signals measured by near-infrared spectrometer

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1. Introduction

Brain is one of the most fascinating systems in universe. As of dynamics, brain system hardly shows any equilibrium states or periodic behavior. According to Strogatz's *Nonlinear Dynamics and Chaos* [1], brain system is classified as *the Frontiers* (or *the unexplored*) with infinite phase dimension and nonlinearity. The brain behavior is typically very complicated in both space and time, but certainly very challenging. In Figure 1, one example of brain signals from different regions obtained by near infrared spectrometers (NIRS) is presented. They are very irregular, nonstationary, and noisy. One of the interesting behaviors of brain signals is synchronization of signals in different cortex regions. Synchronization of firing neurons has been proposed to act as an underlying mechanism of cognitive act in human brain [2]. In this paper, two methods are proposed as analytic tools to quantify the strength of synchronization in the brain signals with the concept of nonlinear dynamics. The brain signals are obtained by optical methods, which is called near-infrared spectroscopy.

2. Method

Near-infrared spectrometer (NIRS)

NIRS based on the scattering properties of biological tissues in near infrared regions. In turbid medium like biological system, photons are strongly scattered and described by Boltzman transport equation. By using frequency-domain NIRS, which was developed by Gratton *et al* [3], absorption and scattering coefficients in biological tissue can be determined. Small-scale biological fluctuations may produce macro-scale spatial fluctuations of tissue optical properties, which was demonstrated that visual stimulus or finger movement induces localized changes in optical properties in visual or motor cortex area [4]. In addition to optical properties, modulation and phase in the frequency-domain near-infrared light can be converted into values for oxyhemoglobin (O_2Hb) and deoxyhemoglobin (HHb) concentrations with the absorption spectrum of tissue chromophores. As presenting hemoglobin concentration, NIRS is similar to functional magnetic imaging (fMRI), but absolute values of both hemoglobin concentrations can be measured by NIRS and only changes of HHb can be monitored by fMRI. Also, NIRS observe fluctuations in brain surface whereas fMRI monitors fluctuations in slice of brain.

Quantification of synchronization

To construct a map of synchronization between different brain region, two methods are presented in this paper. A geometric method, phase portrait was suggested by Wolf *et al* [5] to obtain a functional map of cerebral hemoglobin concentration changes measured by NIRS, which is expected to be applicable for brain signals. Simply, phase portrait is generated by taking the signal of one location as a reference for the other locations like Lissajoux figure. Synchronization of hemodynamic wave between different region is mainly lost for the further locations in their work. Assessment of synchronization via the shape of ellipse in phase portrait has big advantages in physiological data. First, it is robust to shift in natural frequency in physiological data, such as the heart rate. Cross-correlation study or fast Fourier transform analysis is often disturbed by such unstable natural frequency. Secondly, phase portrait has dynamics in both space and time. Elbert *et al* [2] comment that cognitive action must be reflected in neural dynamics in both space and time, which means it is not only important to identify the neural assembly but also crucial to be able to depict its temporal dynamics. NIRS combines good temporal resolution (10-50ms) with a spatial resolution of the order of 5mm [4]. Therefore, the analysis in phase portrait may provide a useful tool for the study of synchronization process in different brain regions.

Second method is using the concept of phase synchronization for the analysis of noisy signals, which was presented by Tass *et al* [6]. Classically synchronization of two periodic weakly coupled oscillators is understood as phase locking and the locking condition reads $|\theta_{nm}(t)| < const, where\ \theta_{nm}(t) = n\phi_1(t) - m\phi_2(t)$, n and m are some integers, $\phi_{1,2}$ are phases of two oscillators, and Θ_{nm} is relative phase. Accordingly, synchronization of neuronal activity between remote areas reflects phase locking between brain signals, which was magnetoencephalography (MEG) signal in their case. To characterize the strength of synchronization, they define a phase synchronization index

(*PSI*) or n:m synchronization indices by the deviation of the actual distribution of the relative phase from a uniform one based on Shannon entropy in information theory. Now we can analyze our NIRS signal from different brain region by use of *PSI*. To define a phase of real number signal, imaginary parts corresponding to signal can be created by Hilbert transform [7]. If we subdivide the measurement into N subintervals, we can associate a probability p_i with the ith subinterval containing particular range of possible outcome followed by evaluation of the Shannon entropy, $S = -\sum_{i=1}^{N} p_i \ln p_i$. Then *PSI* can be evaluated as an index of synchronization of two signals with $PSI = (S_{\max} - S)/S_{\max}$ defined by Tass et al.

3. Discussion

Two methods are suggested here as analysis tools for synchronization between remote brain signals obtained by near-infrared spectroscopy. Phase portrait method is very straightforward and visual to monitor cortico-cortical synchronization, whereas phase synchronization index is very rigorous and can distinguish chaos from noise. With the surface information measured by NIRS, both methods enable us to analyze the spatial-temporal dynamics of brain signals. However, whether synchronization predicted by one method will match with the prediction by the other or not is still in question. By definition, phase in phase portrait and one in *PSI* are different because the first one means a particular stage in phase space and the latter one is phase in complex number. In addition, as we handle real physiological data, the way of filtering and normalization of raw data should be carefully chosen before we input the signals into our synchronization toolbox.

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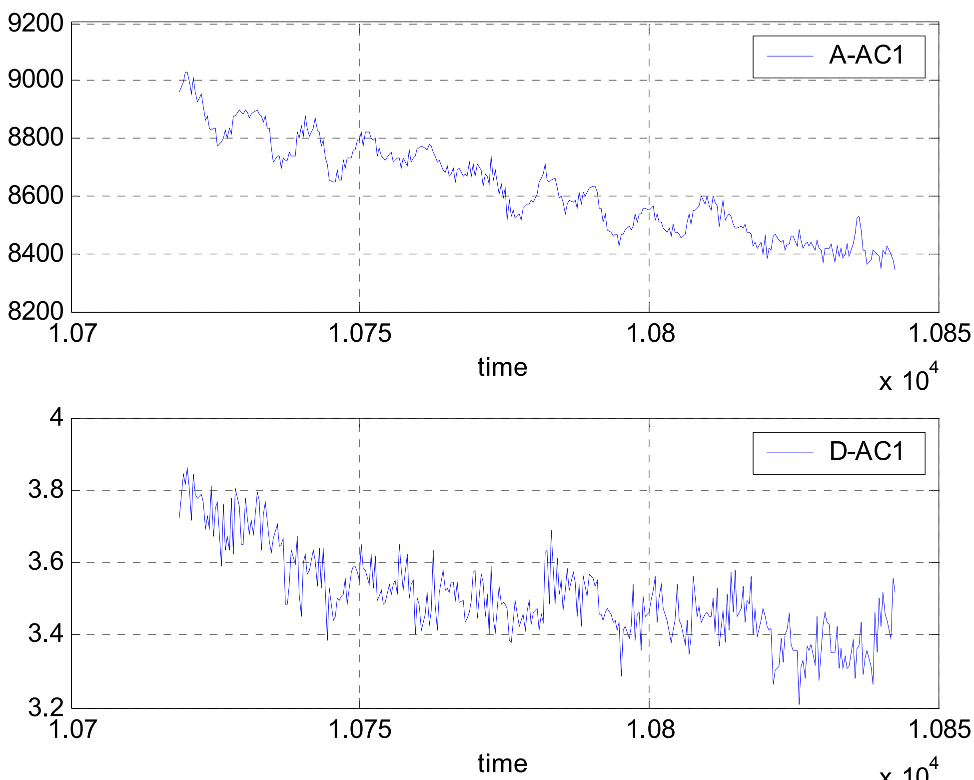

Figure 1. Intensity of near infrared penetrated different brain tissue, which are associated with brain or other physiological activity. Power spectrum analysis reveals chaotic behavior of those signals.