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The Analysis of Brain Activity in Wakefulness and Deep Sleep States from a dog EEG

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We obtained an EEG from a dog in a deep sleep and a wakefulness state. The change of the spectral distribution, the standard deviation and the Poincare section constructed from the delay map were found between the two states. The many couplings between neurons in the wakefulness state cause various frequency modes. Some of the coupling are weakened in the deep sleep state, so the fundamental mode and its first harmonics are excited. The sequential decrease of the a-value from the wakefulness to the deep sleep state shows that entropy increases in the deep sleep state. The lower EEG activity in the deep sleep state can be observed from the value of SD which is smaller than the value in the wakefulness state. In the deep sleep state the delay map for a shape is similar to a quadratic shape, and the shape remains unchanged during the deep sleep state. However, in the wakefulness state, although the quadratic shape remains unchanged, it is rotated or translated in a random fashion.

I. INTRODUCTION

The mammalian brain is one of the most complex systems encountered in nature. It is made of billions of cells endowed with individual electrical activity and interconnected in a highly intricate network. The average electrical activity of a portion of this network may be recorded in the course of time and is called an electroencephalogram (EEG). The EEG reflects the sum of elemental self-sustained neuronal activities over a relatively long period. The circadian rhythm, such as rest and activity, is the self-controlled biological clock-function which is so familiar and so clearly coupled to the cycle of night and day. It is the mechanism for the interaction between the bio-system and the surrounding system. This time-pacemaking function is one of the main biological functions. Also, it has evolutionary information, and it is controlled by the function of the cells in the suprachiasmatic nucleus in the brain. The gene level (period gene, timeless gene) and the activity of the cell, the eclosion and the locomotion of the Drosophila melanogaster, even more the ultradian rhythm in the courtship song of Drosophila (male) , and the behavior level (wakefulness and sleep) have been researched so far.

The purpose of this paper is to characterize the two different main states of the circadian rhythm: wakefulness and deep sleep. The EEG signal from a dog is obtained and analyzed in terms of both linear and nonlinear analysis. Experimental techniques are briefly mentioned in Sec. II and EEG signal analysis is given in detail in Sec. III. Finally a brief conclusion is given with a few discussions in Sec. IV.

II. EXPERIMENT

Before going to sleep, the dog, a female, was connected to an EEG machine in a shielded room. The machine settings were low linear frequency = 1 Hz and high linear frequency = 30 Hz. A 60 Hz notch filter was employed. The behavior of the dog was checked by a video camera. In this experiment, a computerized electroencephalograph was used to measure the EEG signal from the dog in both the wakefulness and the sleep stage. The instrument consisted of EEG-amplifier, an 8-bit analog to digital converter, and an EEG-computer interface and sampled scalp voltage at 1 electrode at a rate of 250 Hz. Two silver chloride cup electrodes were placed, using a conductive paste, on the left part 4 cm distant from the vertex and at the vertex as a reference, respectively, as shown in Fig. 1. A segment of the time series data appears in Fig. 2.

III. ANALYSIS

Five EEG data sets were obtained with 4-ms sampling time and 4096 data points. Fast Fourier transform of each set was performed, and the results were overlapped as shown in Fig. 3. The power spectrum

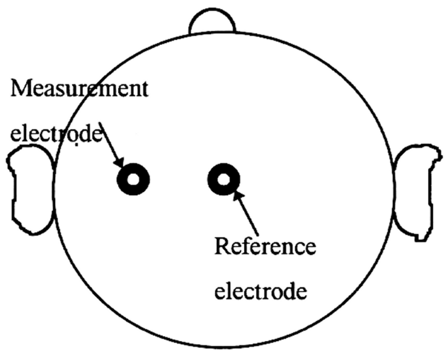

Fig. 1. Electrode placement used in this study.

of the time series data showed activity at all observable frequencies. Figure 3 (a) shows that the power spectrum has its largest value in the range of 2 ∼ 5 Hz and decreases rapidly with increasing frequency in the wakefulness state. However, Fig. 3 (b) shows that the power spectrum has two dominant peaks in the ranges of 4 ∼ 7 Hz and 10 ∼ 11 Hz and is spread out in the deep sleep state. The linear global model of EEG waves is much more involved than the simple linear string [1–3]. For example, multiple long-range fiber systems cause multiple branches of the dispersion relation, and distributed propagation velocities cause selective damping of macroscopic modes. In the wakefulness state, plenty of modes are excited, leading to one large peak with a quickly decreasing pattern. This may be due to both long-range and short-range interactions in the neural system of the neocortex. However, in the deep sleep state, a fundamental mode and its first harmonic are clearly excited, which means that either the long- or the short-range interaction in the neural system may turn off during deep sleep.

The a-value in the $\frac{1}{f^a}$ structure of the power spectrum was obtained by the measurement of the mean slope in –ln (frequency) power spectral space such as $(\ln(f), -\ln P(f))$ at the range of f from 3 to 27 Hz, as shown in Fig. 4. Note that the a-value is inversely proportional to the correlation dimension [4] and approximately inversely proportional to the negative of the Shannon entropy [5] because the correlation dimension is proportional to the Shannon information and information is defined as the negative of the Shannon entropy which is a measure of the lack of knowledge. The above-mentioned information can be regarded as a measure of the knowledge of the observer about the question of which event of the sample set is to be expected if only the probability distribution in phase space is known. In the wakefulness state, the a-value is about 3, as shown in Fig. 4 (a). However in deep sleep state, it is about 1, as

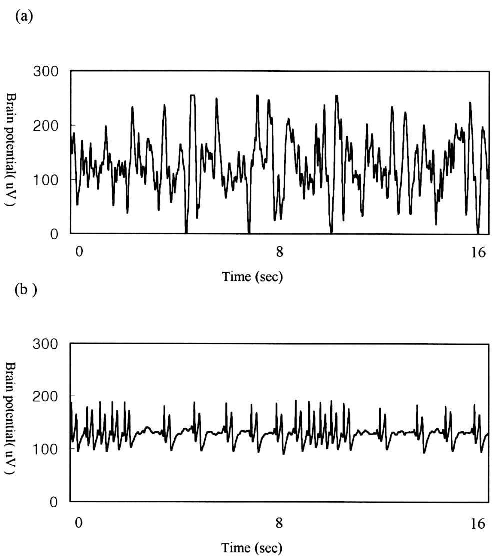

Fig. 2. EEG data in (a) the wakefulness and (b) the deep sleep states (The vertical axis is in arbitrary units).

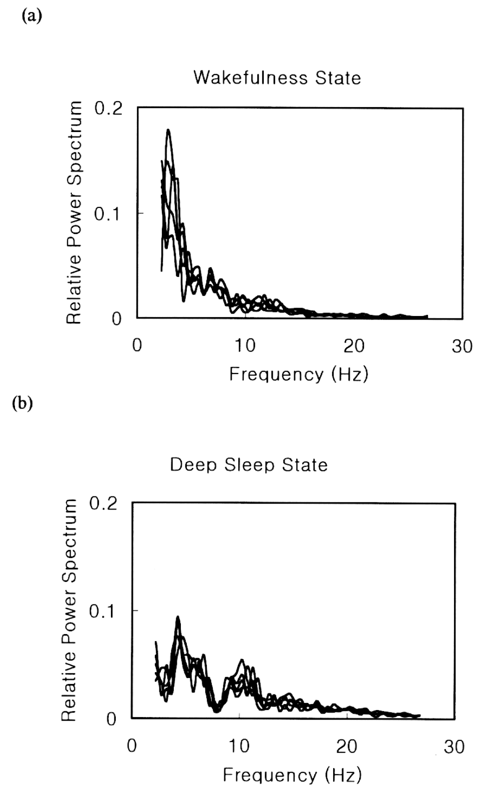

Fig. 3. Power spectrum of the EEG signal in (a) the wakefulness and (b) the deep sleep states.

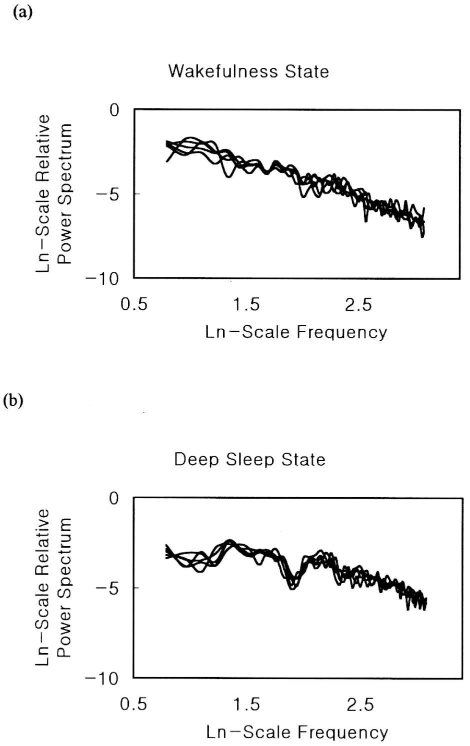

Fig. 4. The graph of the power spectrum plotted on a ln-ln scale in (a) the wakefulness and (b) the deep sleep states.

shown in Fig. 4 (b). The slope of each line was obtained by averaging over the entire frequency range in Fig. 4. The sequential decrease of a-value from wakefulness to deep sleep is demonstrated in Fig. 5, which indicates that entropy increases in deep sleep state. The standard deviation SD is evaluated by the following equation:

$$SD = \frac{1}{N}\sqrt{\sum_{i=1}^{N}(\Phi_i - m)^2} \quad (1)$$

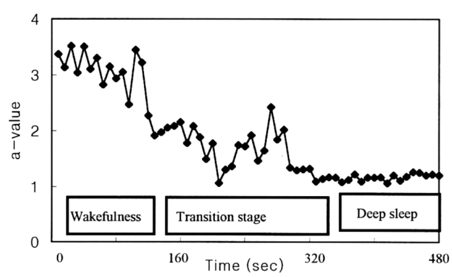

Fig. 5. The a-value transition from the wakefulness to the deep sleep states.

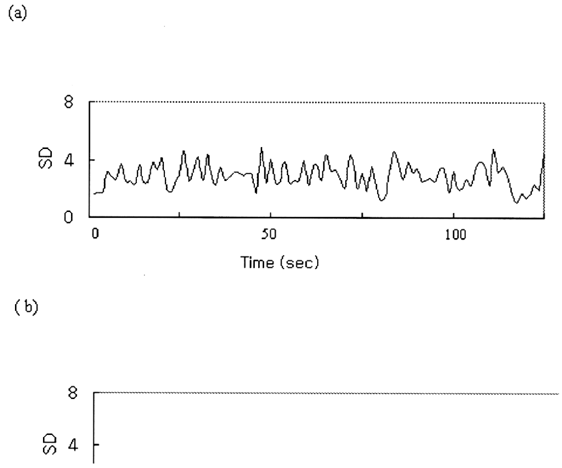

Fig. 6. Standard deviation(SD) in (a) the wakefulness and (b) the deep sleep states.

where m and N are the time average of the EEG and the total number of data points, respectively. In the wakefulness state, SD is in the range of $2 \sim 4$, and in the deep sleep state, $0.5 \sim 1.5$, as shown in Fig. 6. The lower EEG activity in the deep sleep state than in the wakefulness state can be observed from the small value of the SD. The spectrum of the wakefulness state of the dog has a strong lower frequency distribution with higher intensity while that of the deep sleep state has more higher

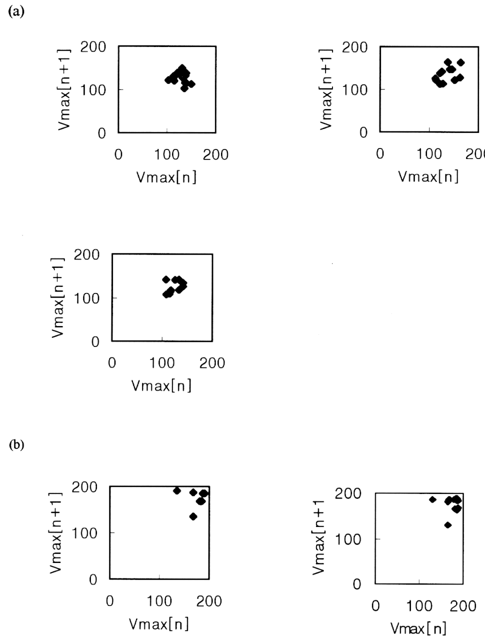

Fig. 7. Poincare section constructed from the EEG in (a) the wakefulness and (b) the deep sleep states.

frequency components with lower intensity. This contradicts strongly the observation made on humans where one would expect the opposite, which is surprising because humans and dogs are both mammals. The cause of this difference should be studied further.

In order to construct the first return map, we sampled the maximum values V[1], V[2],.....,V[n] from the EEG signal and then formed an experimental delay plot (V[n],V[n+1]) [6–9]. Figure 7 (a) shows that a quadratic shape is rotating or moving in a random fashion at different times in the wakefulness state. Figure 7 (b) shows that a quadratic shape remains unchanged for the entire time period in the deep sleep state.

The dynamic rule of neuronal firing can be extracted from the shape of the first return map. This quadratic shape has something to do with the notion that the second order nonlinearity plays an important role in the deep sleep state. Furthermore, the unchanged quadratic shape in the sleep state provides us the fact that all the information pathways from the sensory system are off and only internal degrees of freedom can be excited, resulting in a stationary state. However, in the wakefulness state, all the sensory organs are in the alert state, and the first return map can be changed at any time.

IV. CONCLUSION

In order to analyze the two different states of circadian rhythm, wakefulness and deep sleep, we obtained an EEG signals from a female dog. The spectral distribution, the standard deviation, and the delay map from both EEG signals provided us the fact that they can be distinguished from each other.

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