수면박탈이 각성 뇌파의 양수 리아프노프 지수에 미치는 효과에 관한 연구

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Effects of Total Sleep Deprivation on the First Positive Lyapunov Exponent of the Waking EEG

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Abstract

Sleep deprivation may affect the brain functions such as cognition and, consequently, dynamics of the EEG. We examined the effects of sleep deprivation on chaoticity of the EEG. Five volunteers were sleep-deprived over a period of 24 hours. They were checked by EEG during two days, the first day of baseline period and the second day of total sleep deprivation period. EEGs were recorded from 16 channels for nonlinear analysis. We employed a method of minimum embedding dimension to calculate the first positive Lyapunov exponent. For limited noisy data, this algorithm was strikingly faster and more accurate than previous ones. Our results show that the sleep deprived volunteers had lower values of the first positive Lyapunov exponent at ten channels (Fp_1, F_4, F_8, T_4, T_5, C_3, C_4, P_3, P_4, O_1) compared with the values of baseline periods. These results suggested that sleep deprivation leads to decrease of chaotic activity in brain and impairment of the information processing in the brain. We suggested that nonlinear analysis of the EEG before and after sleep deprivation may offer fruitful perspectives for understanding the role of sleep and the effects of sleep deprivation on the brain function.

1. Introduction

Total sleep deprivation is known to cause various degrees of monotonic decrease in performance of a very broad range of variables including vigilance, reaction time, arithmetic computations, short-term and long-term memory, psychomotor tasks, and logical reasoning tasks. The longer the time period of previous wakefulness is, the greater the decrease in the performances is (Horne 1978; Corsi-Cabrera et al., 1996).

Recent progress in the theory of nonlinear dynamics has provided new methods for the study of time-series data from human brain activities. In the dynamical aspect, the brain is assumed to be a dissipative dynamical system. The distinct states of brain activity had different chaotic dynamics quantified by nonlinear invariant measures such as correlation dimensions and Lyapunov exponents (Babloyantz and Destexhe 1987; Babloyantz 1988; Röschke and Aldenhoff 1991; Fell et al 1993). Therefore, we can investigate the brain function by understanding the dynamical properties of the brain using nonlinear analysis of EEG.

In this paper, we investigate the cognitive dysfunction after sleep deprivation using nonlinear analysis of EEG. We estimate the first Lyapunov exponents of the EEG and compare the values in the whole brain region before and after sleep deprivation. The changes of dynamical properties of EEG at different channels may give the fruitful key to understand the role of sleep and the effect of sleep deprivation on the brain function. In Section 2, we explain the procedure for reconstructing brain dynamics from an EEG and for analyzing the EEG by nonlinear methods and algorithm for determining the proper embedding dimension and for compensating for both noise contamination and edge effects. The first Lyapunov exponent is also defined and discussed. Section 3 briefly presents the procedure for recording data. Section 4 shows the differences in the values of the first Lyapunov exponent before and after sleep deprivation. In section 5, we discuss our results in the dynamical and physiological view. Our conclusions are given in Section 6.

2. Theory and Algorithm

Lyapunov exponents estimate the mean exponential divergence or convergence of nearby trajectories of the attractor. We estimate the first positive Lyapunov exponent with minimum embedding dimension method. In our new algorithm, we calculate the first positive Lyapunov exponent L1 in the minimum embedding dimension. We determine the minimum embedding dimension by using the calculation method, presented by Kennel et al. (1992), which is based on the idea that in the passage from dimension d to dimension $d+1$, one can differentiate between points on the orbit that are "true" neighbors and those on the orbit which are "false" neighbors. A false neighbor is a point in the data set that is a neighbor solely because we are viewing the orbit (the attractor) in too small an embedding space ($d<d_{\min}$). When we have

achieved a large enough embedding space ($d \geq d_{\min}$); all neighbors of every orbit point in the multivariate phase space will be true neighbors. We demonstrated that for limited noisy data, our algorithm was strikingly faster and more accurate than previous ones (Jeong et al. 1997; Jeong et al., 1997).

We calculate the first positive Lyapunov exponent L1 by applying a modified version of the Wolf algorithm (Wolf et al., 1985) and by following a proposal by Frank et al. (1990). Essentially, the Wolf algorithm computes the initial vector distance *di* of two nearby points and evolves its length at a certain propagation time. If the vector length *df* between the two points becomes too large, a new reference point is chosen with properties minimizing the replacement length and the orientation change. Now, the two points are evolved again and so on. After *m* propagation steps, the first positive Lyapunov exponent results from the sum over the logarithm of the ratios of the vector distances divided by the total evolving time:

$$L_1 = \frac{1}{m} \sum_{i=1}^{m} \frac{\ln \frac{df_i}{di_i}}{\mathrm{EVOLV} \cdot dt \cdot \ln 2} \quad (\text{bits/sec})$$

Where *dt, di,* and *df* are the sampling interval, and the initial and the final separations between the points in the fiducial trajectory and in the nearest-neighbor trajectory separated in time by i^{th} EVOLV step, respectively (Wolf et al., 1985).

3. Methods

Five female volunteers, who are between 27 and 30 years old, participated in the experiment. They were free of sleep complaints and had normal sleep habits, as assessed by questionnaire. EEG was recorded during resting wakefulness with closed eyes under two conditions: 1) in the morning after deep sleep for baseline 2) in the morning (between 8:00 and 10:00 A.M.) after total sleep deprivation for one night.

The EEGs were recorded from the 16 scalp loci of the international 10-20 system. With the subjects in a relaxed state with closed eyes for 32.768 seconds of data were recorded and digitized by a 12-bit analog-digital converter in an IBM PC. Recordings were made under the eyes-closed condition in order to obtain as much stationary EEG data as possible. The sampling frequency was 500 Hz. Potentials from 16 channels (F7, T3, T5, Fp1, F3, C3, P3, O1, F8, T4, T6, Fp2, F4, C4, P4, and O2) against "linked earlobes" were amplified on a Nihon Kohden EEG-4421K using a time constant of 0.1 sec.

4. Results

The average values of the L1 and the standard deviations for the subjects under two conditions: 1) in the morning after deep sleep 2) in the morning after sleep deprivation for one night are summarized in Table 1. Sleep-deprived states had lower average values of the L1 at ten channels, i.e., Fp_1, F_4, F_8, T_4, T_5, C_3, C_4, P_3, P_4 and O_1 compared with baseline values.

5. Discussion

Our results indicated that the chaoticity of EEG decreased at several regions of the brain, that is, central, parietal, left prefrontal, left posterior temporal, left occipital, right frontal and right anterior frontal area. This means that the sleep-deprived brain processes informations deficiently and the neural networks are less flexible in these areas. These regions of the brain include the reticular activating system, thalamus, striatum, temporoparietal cortex and frontal cortex (Mesulam, 1981). These regions coincide with the key structure of attention and arousal. We suggested that these areas should be the key to the etiology of cognitive decline by sleep deprivation. We expect that nonlinear analysis will give us a deeper understanding of role of sleep in ways which are not possible by conventional power spectral analysis.

6. Conclusion

In this study, our result demonstrated that total sleep deprivation for one night affects the dynamical properties of the brain. Our result shows that the sleep-deprived female volunteers had lower values of the first positive Lyapunov exponent at 10 channels compared with baseline values.

Our result is a preliminary finding, because the number of subjects is so small. Although our present study is in a fundamental stage of development, its clear result encourages further investigation of the chaoticity and complexity of the brain in sleep-deprived states. Especially, nonlinear measures of the electrophysiological activity in the brain may offer unique and fruitful perspectives for understanding important features of the role of sleep and the effects of sleep deprivation on the brain function.

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Location	after deep sleep (N=5)		after sleep deprivation (N=5)		*P*
	Mean	SD	Mean	SD	
F3	3.9180	0.901	2.4300	0.313	NS
F4	4.1580	0.535	3.5980	0.357	0.0433
F7	4.4940	0.565	3.7720	0.377	NS
F8	4.5380	0,122	3.5760	0.332	0.0433
Fp1	4.2360	0.406	2.2700	0.589	0.0431
Fp2	4.0380	0.662	3.2880	0.244	NS
T3	4.1240	0..323	3.4580	0.330	NS
T4	4.6420	0.689	3.4920	0.268	0.0431
T5	4.3000	0.293	3.2900	0.224	0.0431
T6	4.3040	0.382	3.2960	0.381	NS
C3	4.0540	0.365	2.1760	0.162	0.0431
C4	4.5209	0.448	3.3180	0.120	0.0431
P3	4.2940	0.392	2.4040	0.346	0.0431
P4	4.5640	0.369	3.5640	0.182	0.0431
O1	3.8580	0.289	2.4860	0.454	0.0431
O2	3.9260	0.730	3.8160	0.055	NS

NS: Not significant (Wilcoxon matched-pairs signed-ranks test)

Table. 1 The average values of the L1 and the standard deviations for the subjects under two conditions: 1) in the morning after deep sleep 2) in the morning after sleep deprivation for one night.