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비선형 분석을 이용한 정신활동 상태에 따른 EEG의 변화에 관한 연구

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Some Mental Activity Which Can be Discriminated Only on Non-linear Analysis of EEG Measure

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요 약 : 이 연구의 목적은 선형적 주파수 분석방법으로는 구별되지 않는 감정상태와 인지상태의 EEG를 구별할 수 있는 새로운 방법을 제안하는 것이다. 건강한 피험자들의 EEG를 세가지 다른 조건-눈을 감고 편안히 쉬고 있는 상태, 음악을 듣고 있는 상태, 눈을 감고 단순한 뺄셈 연산을 수행하고 있는 상태-에서 각각 측정하였다. 점관점 상관차원 (PD2) 방법을 이용하여 각 정신상태에 따른 EEG를 분석하였다. 연산과제를 집중해서 수행했다고 보고한 집단이 그렇지 않다고 보고한 집단보다 더 높은 PD2 값을 통계적으로 유의하게 나타내었다. 또한 음악을 듣는 과제에서 높은 점수를 얻은 집단이 그렇지 않은 집단에 비해 상대적으로 낮은 PD2 값을 나타내었다. 같은 EEG 신호에 선형 분석 방법인 주파수 분석 방법을 적용하여 보았으나, 유의한 차이를 보이지 않았다.

Abstract : The purpose of this study was to find the way of discriminating EEG for some mental activity, which are not characterized within linear spectral analysis but with non-linear analysis. We have investigated the way of characterizing EEG changes during emotional and cognitive states in healthy volunteered subjects who responded to three designed status, in which the subjects were relaxing with ease and eyes closed, listening to music and computing a simple subtraction with eyes closed. Especially, we estimated EEG dimensional complexity by Skinner's point-wise correlation dimension(PD2) method for each mental states. As a result it has been found that the subjects, who responded that they had concentrated well during the arithmetic task, show higher PD2 in their non-linear EEG measures, in comparison with the subjects who responded that they had not concentrated during the task. This highness of PD2 is also significant in statistical analysis. A subject who had the highest score in evaluating the intensity of induced emotion during emotional task shows significantly lower PD2 in statistical analysis than other subjects who had lower scores. Linear spectral analysis was also performed on these data. However, they did not show any significant difference. Only non-linear dynamical analysis shows the significantly different result on these mental status.

Key words : EEG, Point-wise correlation dimension, Non-linear dynamics.

INTRODUCTION

It has been well known that specific cortical and subcortical brain system is utilized and have been differentiated by regional electrical activities according to the

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associated mental states, for example, emotional states, cognitive states, etc. Since difference in activities of the brain causes difference in characteristics of EEG, it has been attempted to investigate the brain activity through analyzing EEG. Unlike periodic phenomena, which are characterized by a limited number of frequencies, analysis of non-linear dynamics shows a broad band spectrum [1].

It has been believed that it is valid, as a first approximation, to conceive of local neural networks in the cortex as deterministic dynamical systems [2] and to interpret the correlation dimension as providing information about cortical dynamics. This allows us to use the mathematical theory of non-linear systems to analyze EEG. Since Nan and Jinghua [3] had reported an increase in correlation dimension (D2) during mental arithmetic, there was some evidence for a relation between task complexity and higher D2 [4,5]. Stam et al. found D2 increased during both eyes open and during arithmetic conditions compared to the eyes closed passive condition [6]. Aftanas et al. reported that both negative and positive emotions occurred with higher values (at some posterior locations) of EEG point-wise correlation dimension (PD2) estimates compared to the neutral viewing condition [7].

On the basis of this current trend, we have tried to describe how the emotional and cognitive arousal which are one of popular daily mental activity reflect the change of PD2 value of EEG measures. Especially, the purpose of this study was to find the way of discriminating EEG for some mental activity, which are not characterized within linear spectral analysis but with non-linear analysis.

METHODS

1. Subjects and EEG Recordings

Ten healthy volunteered subjects were right-handed 6 males and 4 females between the age of 22 and 40 years (mean ages: 26.5 years). Most subjects were students from biomedical engineering department and colleagues of the study. Prior to the experiment the subjects were informed verbally about all the aspects of the experimental procedure and then asked to sign an informed consent.

The subjects were free of any medication. EEG was recorded from following six sites using Ag/AgCl electrodes according to the international 10-20 system: F7, F8, C3, C4, T5, T6. We chose the reference point as A1 at left ear. At the recording channels the signals were amplified with a bandwidth from 0.016 Hz to 60 Hz. EEG recordings were conducted using Beckmann EEG system in the electrically shielded room. EEG data were digitized using A/D converter in the PC connected to the Beckmann EEG system. Sampling frequency was set to 200 Hz and the resolution was set to 12-bit during A/D conversion.

2. Designed status

EEG was recorded for 3 minutes under three designated conditions: 1)rest state with closed eyes; 2)induced emotional state listening to Mozart's Requiem with closed eyes. 3) cognitive state computing serial subtraction 7s from 1000 with closed eyes. Time intervals between three conditions were 10 minutes. During listening to the music the subjects were asked to try to induce emotion. After the experiments the subjects reported self-evaluation about how much their emotion was induced during listening to music, and whether they had concentrated on computing or not during mental arithmetic activity.

3. Calculation of point-wise correlation dimension

The algorithm for calculation of PD2 has been proposed by J.E. Skinner, based on suggestions by G. Meyer [8,9]. The original algorithm suggested by Grassberger and Procaccia to estimates the correlation dimension(D2) assumes that the time series are stationary state [10].

However, the biological data are not stationary, which are continuously changed according to their environments. PD2 is designed to measure D2 of the non-stationary data. It can also trace the temporal changes of D2, and the algorithm is much more efficient to estimate a correlation dimension within a short time. The algorithm of estimating PD2 is as followings: 1) D2 is computed for every n-th d-dimensional point in phase space. 2) In each computed point, the criterion, that whether if the D2s converge with increasing embedding dimension, is implied. The correlation integral in Skinner's model to estimate PD2 is

$$C(n, r, n^*_{ref}) \sim r^{D2} \quad (1)$$

where n is the number of data points, and r is the scaling range, and n^*_{ref} is an acceptable reference vector showing scaling within its own sub species. C is correlation integral graph, and D2 is the corresponding correlation dimension. We found that D2s of several EEG

data converged clearly at dimension 22 as increasing embedding dimension from 2 to 30. Thus the embedding dimension was set to 22 in the present study.

The time delay in the reconstructed vector was chosen inverse of the sampling frequency (1/200). Using the program which had been programmed in MATLAB by one of the authors of the present paper, we estimated PD2 values of the time series of EEG data for each consecutive 1 minute (12000 points) at the six electrode sites for each three designed status previously mentioned. Linear spectral analysis was also performed, and four different frequency bands were obtained: alpha (8~13Hz), beta (13~29Hz), theta (4~8Hz), and delta (1~4Hz).

4. Statistical analysis

Using program SPSS 8.0, MANOVAs were computed to investigate the effect of electrode location, three conditions and groups of subjects on PD2. Non-parametric statistic method was repeatedly performed to compensate the low number of subjects for the same condition in the above. One Sample T-test which shows how much PD2 of one subject differs from the mean values of each remaining subjects was computed in case of emotional data.

RESULTS

The mean values of the point wise correlation dimension(PD2) over ten subjects during three tasks have shown no significant differences which is able to represent three mental activity, rest state, emotional state and cognitive state in our experiments. Table 1 shows the mean values over ten subjects of PD2 at six electrode sites during three designed status.

A subject who had the highest score in evaluating the intensity of induced emotion during emotional task shows significantly lower PD2 in One-Sample T-test than other subjects who had low score. In One Sample T-test which shows how much PD2 of the subject differs from the mean values of remaining nine subjects. Especially lower values of PD2 were dominant at electrode site F7 ($t=8.203$, $df=8$ $P<0.001$) and F8($t=4.881$, $df=8$, $P<0.001$) located fore frontal lobe. Even though with this experiment it was not successful to verify that PD2 tells emotional state from cognitive state, however, we have

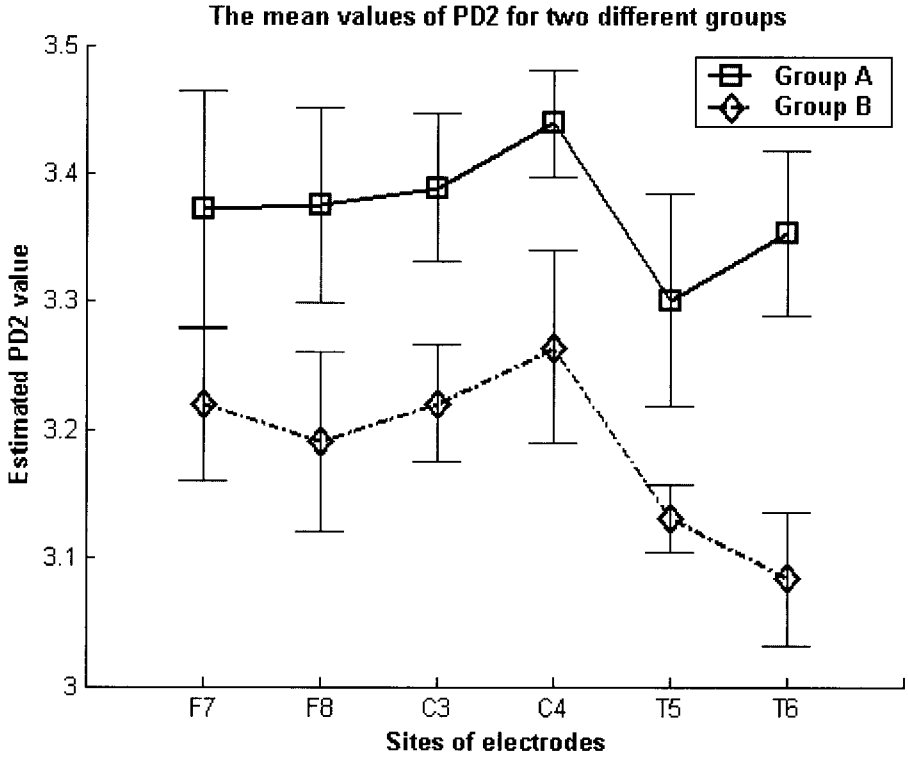

Fig. 1. The mean values of PD2 for two groups. Group A represents the subjects who concentrated during arithmetic task, while group B is for the subjects who responded that they did not concentrate during the task. It shows the PD2 values of group A are much higher than those of group B at all sites. However, only C3 and C4 sites show significant difference in statistical analysis using ANOVA

found PD2 is representative for some mental activity. During the cognitive task PD2 were computed for two separated groups that we called group A and group B. The members of group A answered that they had concentrated during arithmetic task, while the members of group B answered they had not. Seven of ten subjects belong to group A and remaining three of them belong to group B. The mean values of PD2 over group A is higher than those of group B at all electrode sites. Figure 1 shows the mean values of PD2 over group A in comparison with those of group B. Especially the values of PD2 at C3 and C4 for group A are significantly higher than those of group B.

This result implies that the more concentration increases the dimensional complexity of dynamics of EEG measures. It can be said that this result supports several previous results of high PD2 related to attention and intelligence quotients [6]. Also we conjecture that it may be correlated with the synchronicity of local cortical area during a highly concentrated task like mathematical calculation [11].

ANOVAs were computed to check the statistical significance of these results. For only two of six sites, C3 and C4, the P values are significantly low ($F(1,8)=9.545$, $\eta=0.544$, $P=0.015$ at C3; $F(1,8)=5.992$, $\eta=0.428$, $P=0.40$ at C4). It is well known that both of central lobes are related to mathematical activity. The dominance of these two sites agrees with this fact. The crossover analysis finding a significant difference between right and left central parietal lobe was tried during the task. However, it did not obtain any statistical significance. For these two groups, linear spectral analysis also was performed to compare with non-linear analysis. Fast Fourier transform was performed, extracted through overlapping Hamming windows by averaging estimates of spectral power(μV^2) in the following several frequency bands. α band is between 8~13 Hz; θ band is between 4~8 Hz; δ band is in 1~4 Hz and β is in 13~29 Hz. Figure 2 shows the

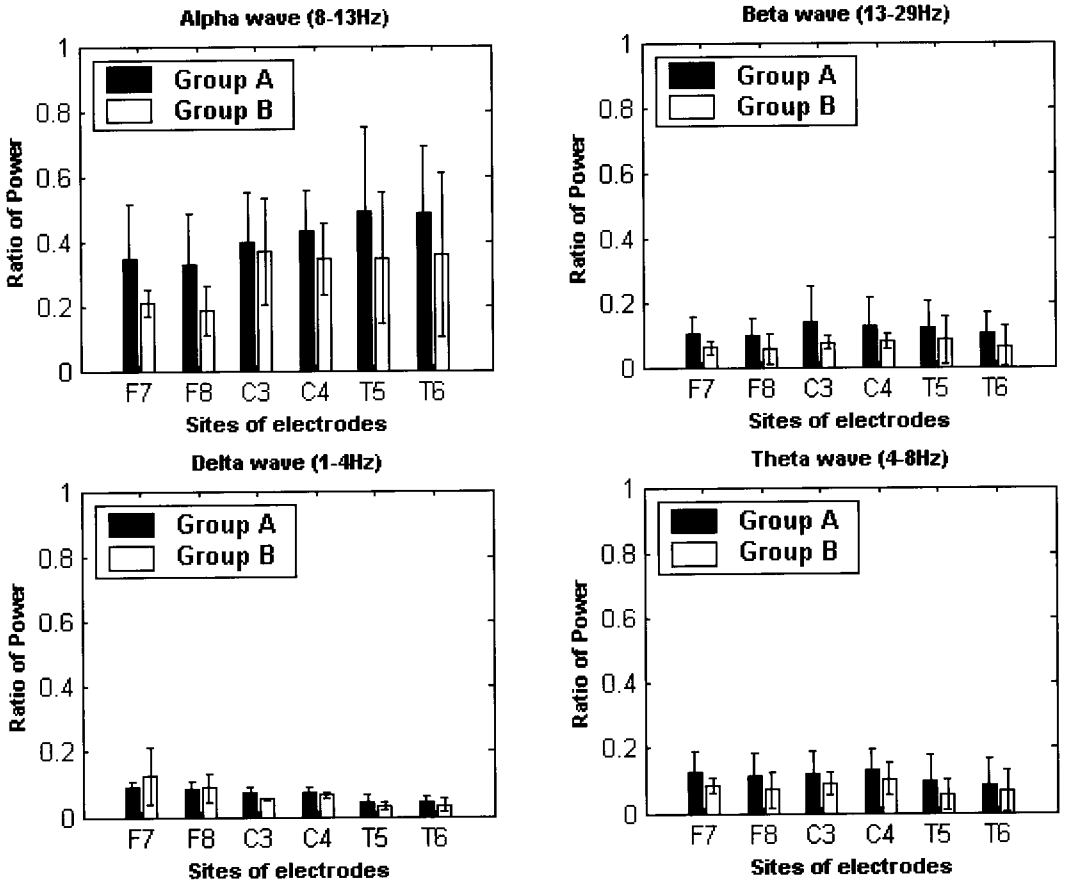

Fig. 2. The power spectrum for four waves, alpha, theta, beta and delta bands. The black bars at every channel are for group A and the white bars are for group B

Table 1. The mean values of PD2 for three states, rest, emotional and cognitive state.
표 1. 세가지 조건, 휴식, 감정, 연산 상태에 대한 PD2의 평균 값.

Site	Rest	Emotion	Calculation
F7	3.36	3.30	3.33
F8	3.30	3.23	3.32
C3	3.31	3.27	3.31
C4	3.38	3.35	3.39
T5	3.28	3.25	3.25
T6	3.24	3.18	3.27

ratios of four each wave to total power for two groups in averages over each group members. In the figure, the black bars at every channel are for group A and the white bars are for group B.

In case of α, β and θ waves, it can be seen that the mean power ratios of group A are higher than those of group B at six electrode sites. In case of delta wave, the same is true except at the site F7. For all bands and all sites ANOVAs also were computed to check whether these results of linear analysis might have statistical significance. But these linear results did not obtain any significant P value for all bands and sites.

The mental activity related to concentration seems not to be characterized within linear spectral power analysis. However, the non-linear results shows significant differences in statistical analysis. As a result, we can say that the dimensional complexity reflects the degree of concentration during some mental activity. The more concentration gives the higher dimensional attractor of dynamics.

DISCUSSION

In the present study, the higher values of PD2 at electrode site C3 and C4 for group A, who concentrated on arithmetic task, seem to reflect the fact that the parietal cortical area is involved in arithmetical process [12]. Anatomically, C3 and C4 are located around central parietal cortical area. Also this study clearly shows that the increase of PD2 measuring the complexity does not depend on whether their results of the computations are right but on whether the individual subjects concentrate on their computational processes. This is in agreement with the previous study [6] which showed that the score estimating the rightness of the result of computation was not correlated with the increase of PD2. Conjecturing that the sophisticated subjects may easily concentrate than other non sophisticated subjects, it can be said that this result also supports the reports [5] of higher PD2 for the subjects who have higher intelligence quotient or who are sophisticate in music performance [13].

Through this kind of comparison, in interpretation of dynamics of brain, the higher PD2 can be used as an indicator measuring concentration during cognitive activity including arithmetic task. The lower value of PD2 at frontal lobe for the subject, who has high score in evaluating the intensity of induced emotion, looks to be based on the fact that frontal lobe is functionally involved in emotional process. Some PET scan studies reported that during human subject felt deep sorrow the frontal cortical area was less

activated and subcortical area was more activated [14]. In the present experiment the music was not enough to induce a kind of emotion for all subjects, so only one of ten subjects felt sad listening the music. However, it can be interpreted that the low PD2 of one subject comes from the change of pure factor related to a controlling emotional process, because other additional common factors, which participate in information process of the music, are cancelled for the two subject group; one subject whose emotion was induced and the other remaining 9 subjects whose emotions were not. Also this result gets into line with the earlier many reports for the low PD2 for emotional state [7].

Based on this result, we conjecture that the low PD2 during emotional process occurs especially at prefrontal cortical area and the low PD2 are deeply related to the inactivity of prefrontal cortical area in comparison with the PET scan research [14]. That is, less dynamical complexity may correspond to low activity of the special cortical area. It is expected that the experiment designed with further rigorously developed protocol and many electrode sites could demonstrate this point clearly in future studies.

With the help of non-linear analysis we could see what linear spectral analysis could not show in the present study. The results which are significant also in statistical analysis, the low PD2 at F7 and F8 for one subject during induced emotion and the higher PD2 at C3 and C4 during arithmetic task, are blind up to linear spectral power analysis. The result of the present study in combination with the results of previous reports in this field strongly supports the idea that decrease and increase of PD2 are associated with different type of mental activity which is never discriminated on linear spectral power analysis [7].

Finally, from many earlier studies on nonlinear analysis of EEG measure including our present result we carefully speculate that the increase of PD2 may strongly depend on the local activity which has much greater coherency within a short range and has been less synchronized in a long ranged cortical area. In view point of neural network, during a cognitive task many selective neurons in the special cortical column, which participates in the cognitive task, emit spike at rate 20/sec [15, 16]. This rate is much higher than the spontaneous rate that is around 4~5/sec. Spontaneous activity is global activity. In physical viewpoint the local activity needs much energy than global synchronized activity, so it induces a kind of excited mode that has many nodes in phase space and implies more complexity of dynamics. This speculation should be simulated modeling real neural network which can generate non-linear time series by spike of individual neurons in a special column, furthermore, in many cortical area in future work. This kind of approach may shed light on finding a connection between neural networks and non linear EEG measure of human.

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