Differences of EEG between Eyes-Open and Eyes-Closed States Based on Autoregressive Method

Ling Li, Lei Xiao, and Long Chen

Abstract—Autoregressive (AR) power spectral density estimate method was used to analyze the electroencephalogram (EEG) signals in eyes-open and eyes-closed states. From the topographical distributions of delta, theta, alpha, and beta power spectrum, these two states can be clearly discriminated. In these two states, frontal areas were activated in delta power, both frontal and occipital areas were activated in theta band, and occipital areas were activated in alpha and beta bands. These four bands had significantly higher power in frontal, parietal, and occipital areas when eyes were close. The results also implied that the optimum order of AR model could be more suitable for estimating EEG power spectrum of different states.

Index Terms—Autoregressive (AR) model, electroencephalogram (EEG), optimum order, power spectral density.

1. Introduction

It is well known that there are many differences in EEG signals between the eyes-open state and eyes-closed state. Many researches about EEG signals have been done, such as alpha activity in occipital[1][2] and power spectral analysis of EEG in eyes open/closed state[3]. In 2007, Robert J. Barry had used Fourier transform to analyze EEG signals in eyes-open and eyes-closed states. It was reported that topographic changes were evident in all bands except for alpha, and confirmed the use of mean alpha level as a measure of resting-state arousal under eyes-closed and eyes-open conditions[4].

The methods for dealing with EEG signal have developed very quickly, such as Fourier transform[5], wavelet transformation[6], independent component analysis (ICA)[7], principal component analysis (PCA) methods[8] and so on. Especially, autoregressive (AR) method is prevalently used in analyzing EEG signal[9]. Using AR method to process one channel of recorded EEG data[10][11] has been studied very well. At present, AR method has also been improved in determining optimum order[12][13]. However, it is rare to process and analyze multidimensional EEG signals in eyes-open and eyes-closed states with AR method.

The greatest difficulty of using AR method is how to select the optimum order of AR model. To a small quantity of data, the optimum order can be determined by final prediction error (FPE) method. However, EEG signals we collect are usually vast, so it is difficult to process these signals effectively and directly by FPE method. Furthermore, clinic EEG data are usually continuously recorded with many electrodes at one time. In this way, data become increasingly huge. Therefore, it is more difficult to process signals accurately and directly by FPE method. According to specific recorded EEG, we must first remove the electrooculogram (EOG) and the significant muscle artifact, so that EEG data should be divided into short segments for selecting good data[14]. After preprocessing, FPE method could be used to determine the optimum order in the study of multidimensional EEG signal. Then, we could build multivariate autoregressive models[15] to estimate power spectrum of EEG, and exhibit topographical distributions of two different states.

This paper was organized as follows. Section 2 provides the materials and methods (including stimuli, subjects, EEG measures, preprocessing, and data analysis). Section 3 presents the results of the optimum order, one channel analysis, and multidimensional spectral analysis. Section 4 and section 5 presents the discussion and the conclusions respectively.

2. Materials and Methods

2.1 Stimuli

The experiment was performed in a quiet room. In this experiment, there was a green cross in the middle of the screen of computer. In the eyes-open state, every subject focused his (her) eyes on the green cross with relaxation. In the eyes-closed state, every subject just closed his (her) eyes and sit quietly. And each state would last about 3 minutes to collect enough EEG data.
2.2 Subjects

A total of five healthy, right-handed student subjects (3 males, 2 females) were tested, ranging in age from 18 to 22 years (mean 20). All of the subjects had not any neurological disorders, psychiatric diseases, or were on medication. And all subjects had normal vision and audition.

2.3 EEG Measurements

We collected EEG data by a 128-channel commercial EGI system (SYSTEM 200 EEG/ERP), with impedances of each scalp-electrode ranging from 10 kΩ to 40 kΩ. Scalp-electrode was distributed as shown in Fig. 1. In Fig. 1, the channel location and the electrodes labeled with circles in the experiment were studied in particular. We digitized the data with a sampling frequency of 500 Hz, and processed data with 0.5 Hz to 50 Hz band-pass filter. The reference electrode was located at the vertex of the head (129th electrode). Continuous EEG data with length of three minutes were recorded and for further off-line processing. The artificial noisy signals such as eyes and head movements were removed from the raw data of each subject in the eyes-open and eyes-closed states.

2.4 Preprocessing

The 128 electrodes EEG data were divided into several segments with the length of 2 seconds. If the absolute value of EEG was greater than 50 μV in a segment, then this segment was a bad segment. To each electrode, the quantity of bad segments was counted. The electrodes which had more than 40 bad segments were determined as bad channels. These bad channels data were replaced by the average value of surrounding six electrodes data. As to good channels we only eliminated the bad segments.

2.5 AR-Model Power Spectral Density Estimation

The AR method was used to analyze power spectrum in this research.

The EEG signal \( x(n) \) can be written as

\[
x(n) = w(n) - \sum_{k=1}^{p} a_k x(n-k) .
\]

where \( w(n) \) is the white noise input to the AR model, \( a_k \) is the coefficient of AR model and \( p \) is the optimum order.

The correlative function of \( x(n) \) and \( w(n) \) is

\[
R(m) = E[x(n)w(n+m)] .
\]

Based on (1) and (2), a matrix equation of AR model can be got:

\[
\begin{bmatrix}
R(0) & R(-1) & L & R(-p) \\
R(1) & R(0) & L & R(-p+1) \\
M & M & M & M \\
R(p) & R(p-1) & L & R(0)
\end{bmatrix}
= \begin{bmatrix} \pi \end{bmatrix}
\begin{bmatrix} \sigma_w^2 \end{bmatrix}
\]

where \( \sigma_w^2 \) is the variance of white noise input.

From (3), it is obvious that determining the optimum order \( p \) of AR model is very important. The FPE method can be used to confirm the optimum order:

\[
FPE(p) = \frac{\sigma_w^2}{N + p + 1} \frac{N}{N - p - 1}
\]

where \( \sigma_w^2 \) is the variance estimate and \( N \) is the length of data. A referenced segment must be selected when using FPE method, the variance of which is the closest to the whole EEG data variance. The AR model parameters can be determined by using L-D in the solution of the Yule-Walker equations. The AR spectral power density is computed by

\[
P(f) = \frac{\sigma_w^2}{1 + \sum_{k=1}^{p} a_k e^{-j2\pi fk}}^2 .
\]

2.6 EEG Power Spectral Density Analysis

In this study, the power spectral density of four EEG rhythms was analyzed. There were delta (from 1.5 Hz to 3.5 Hz), theta (from 4 Hz to 7.5 Hz), alpha (from 8 Hz to 13 Hz), and beta (from 13.5 Hz to 25 Hz) rhythms. And four-channel EEG signals were analyzed in specialty, which were 8th, 26th, 60th, and 86th electrodes. In order to observe the topographical distribution of the power of the delta, theta, alpha, and beta rhythms, the topographical distribution of all the subjects were acquired by Eeglab 4.512 software.

<table>
<thead>
<tr>
<th>Ordinal number of electrode</th>
<th>Eyes-closed state</th>
<th>Eyes-open state</th>
</tr>
</thead>
<tbody>
<tr>
<td>8th</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>26th</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>20th</td>
<td>15</td>
<td>11</td>
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<td>28th</td>
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<td>31st</td>
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<td>36th</td>
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<td>43rd</td>
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<td>65th</td>
<td>14</td>
<td>12</td>
</tr>
<tr>
<td>75th</td>
<td>11</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 1: Contrast of the optimum order between open/close states
3. Results

3.1 Optimum Order

The optimum orders of four electrodes (8th, 26th, 60th, and 86th) were shown in Table 1. In Table 1, the variance of all the optimum orders in the eyes-open state was small (77.31), but in the eyes-closed state the variance was large (177). Hence, we considered that the optimum order of EEG AR modeling could be more suitable than fixed order for estimating EEG power spectrum.

![Spectrum](image1)

![Spectrum](image2)

![Spectrum](image3)

![Spectrum](image4)

Fig. 2. The spectrums of four electrodes in two states: (a) the 8th electrode, (b) the 26th electrode, (c) the 60th electrode, and (d) the 86th electrode. The left is the spectrums in eyes-closed state, the right is the spectrums in eyes-open state.

3.2 One-Channel Analysis

Using AR spectral analysis, power spectrums of EEG signal were gained. The spectrums of the four electrodes (8th, 26th, 60th, and 86th) are shown in Fig. 2. The statistic results showed that there were many differences between eyes-closed and eyes-open states. As can be seen from Fig. 2 (a) and (b), the peak values were mainly centered on bands of 1.5 Hz to 3.5 Hz and 4 Hz to 7.5 Hz in the 8th and 26th electrodes. In the 60th (Fig. 2 (c)) and 86th (Fig. 2 (d)) electrodes, the peak values were centered on bands of 8 Hz to 13 Hz and 13.5 Hz to 25 Hz in both states. Comparing two states, the power of delta, theta, alpha, and beta were more intense in the eyes-closed state.

3.3 Multidimensional Spectral Analysis

The topographical distributions of average power of all the subjects are shown in Fig. 3. Each row shows topographical power distribution of every EEG band. The first column shows activity in four bands in the eyes-closed state, the second shows activity in the eyes-open state and the last shows the normalized differences. Based on Fig. 3, the greatest difference between two states was that the power in eyes-closed state was higher than that in eyes-open state, especially in the alpha band. In the delta and theta bands, the power in eyes-closed state was twice of that in eyes-open state. In the alpha band, the power in eyes-closed state was almost decuple of that in eyes-open state. In the beta band, the power of two states was almost equal.

![Topographic Map](image5)

![Topographic Map](image6)

![Topographic Map](image7)

![Topographic Map](image8)

Fig. 3. Topographic maps of different condition: (a) the delta rhythm and (b) the theta rhythm, (c) the alpha rhythm, and (d) the beta rhythm.

In Fig. 3 (a), delta power was activated at the frontal...
areas in both states, but in the eyes-open state the power was almost distributed over the whole fringe of brain. The normalized differences between two states were centered in frontal areas. In the Fig. 3 (b), theta power was mainly activated in frontal and occipital areas. The power was also distributed over the whole fringe of brain in the eyes-open state. The normalization differences were centered on frontal and occipital areas. Alpha power (in the Fig. 3 (c)) was almost centered in the occipital in both states. Both parietal and occipital areas were different between two states at normalization. The distribution of the beta power (in the Fig. 3 (d)) was mainly at back end of occipital areas in both states. After normalization, the difference between two states was also centered in occipital areas.

It was a noteworthy contrast that the activated areas were transferred from frontal areas to occipital areas and from delta, theta, alpha, to beta rhythms.

3.4 Statistic Analysis

The average power value of each subject was also computed in the delta, theta, alpha, and beta bands in both states, as shown in Fig. 4. The average power in the eyes-closed state (Fig. 4 (a)) was obviously higher, especially in the alpha band. In addition, in the eyes-open state (Fig. 4 (b)), the power of four rhythms was decreased along with the increase of frequency. In contrast, in the eyes-closed state, the power of alpha band was fluctuant in some subjects.

![Fig. 4. The average power of the delta, theta, alpha and beta rhythm in two different states: (a) in the eyes-closed state and (b) in the eyes-open state.](image-url)

4. Discussion

This study attempted to discover the differences of EEG signal between the eyes-closed and eyes-open states by AR method and the topographical distribution.

The 8th and 26th electrodes were located in the frontal area and the 60th and 80th electrodes were located in occipital area, so delta and alpha were active in relevant electrodes areas. There were more obvious changes of power distribution either in eyes-open or eyes-closed state in those regions than other regions in Fig. 3.

Usually, the order of AR method was a fixed parameter in the EEG study. However, we obtained the optimum order of every electrode by FPE method. From Table 1, the variance in the eyes-closed state (177) was much bigger than that of eyes-open (77.31). The influences of EEG approximate entropy were big in the different region in the eyes-closed state, while it is small in the eyes-open state\[^{16}\].

So the main component of EEG signal was different in the different areas, especially in the eyes-closed state. In addition, this may imply that the optimum order can denote the brain dynamics characteristic.

The changes of topographical distribution of power between two states were obvious. In standard scores within each electrode, the difference between two states (the last column of Fig. 3) supported the EEG of eyes-closed condition as a baseline\[^{4}\].

In the eyes-closed state the average powers of three subjects were exceptional in the alpha rhythm (Fig. 4 (a)). Alpha rhythm is active at the state of eyes-closed. When people are in the state of relaxation, it will be much more obvious. But alpha rhythm is interdicted when eyes are open\[^{17}\].

5. Conclusions

In this study, we analyzed the differences of EEG signal between eyes-closed state and eyes-open states by AR method. By the method of statistic analysis and topographical distribution of power, we found that the greatest difference between two states was that the power in the eyes-closed state was much higher than that in the eyes-open state. Compared with Fourier transform and other methods\[^{4}\], the optimum order of AR model might be more suitable for estimating EEG power spectrum of different states. The relationship between nearby electrodes in the eyes-open and eyes-closed states will be studied in the future.

References


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