Novel Method to Discriminate Awaking and Sleep Status in Light of the Power Spectral Density

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Abstract. Sleep stages are mainly classified via electroencephalogram (EEG) which involves some prominent characters not only in amplitude but also in frequency. What is more, researchers are using computer assisted analysis to acquire the panoramic view of long duration sleep EEG. However, unlike the empirical judgment, it is fairly difficult to decide the specific values of sleep rules for computer based analysis due to the fact that those values vary with individuals and different distance from reference to signal source on scalps. This paper will introduce a novel method using power spectral density to discriminate awaking, light sleep and deep sleep EEG just according to the features extracted from EEG.

Keywords: PSD, EEG, Awaking, Light sleep, Deep sleep.

1 Introduction

Since the middle of last century, there are great amounts of scientists doing research on sleep, no matter in pathological field, psychological field or physiological field. And the sleep analysis has been applied into several practical projects such as the diagnosis of epilepsy.

And as a world-wide standard rule, the ‘R-K rules’ is always being ameliorated since its birth in Washington, 1968. According to this rule, an epoch-by-epoch approach is strongly recommended in all scoring procedures [1]. In the beginning, this rule was just for doctors and researchers to judge the stages by experience; however, the computer assisted skills started to develop since 1980s together with the development of IT industry. While the problem came that for this technology just for manual judgment, the exact value as the standard for analysis was not so clear that the vague borders between stages made it not easy to complete the discrimination correctly, resulting in the time-consuming process of determining the specific parameters. As three sorts of typical sleep stages, the aim of this paper is to distinguish the states of awaking status, light sleep and deep sleep using power spectral density. We have got to know that the background activity of human body includes black noise (i.e.

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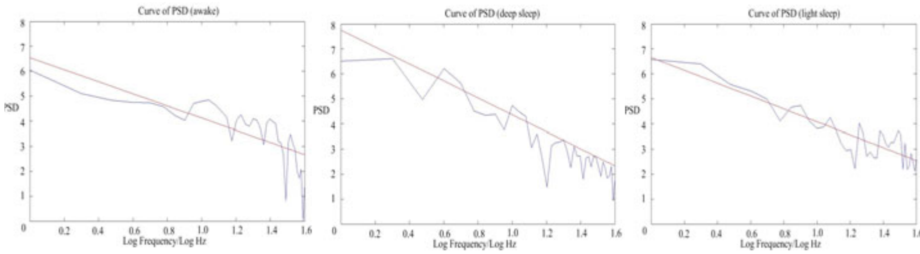
background noise mainly in low frequency), brown noise (i.e. background noise mainly in low and middle frequency) and pink noise (i.e. background noise mainly in relatively higher frequency). The background activity of cerebral cortex in states of rest and slow wave sleep resembles broadband noise. The power spectral density (PSD) then may often conform to a power-law distribution: a straight line in coordinates of log power vs. log frequency [2]. For human race, in slow wave sleep (SWS) PSD decreases at $1/f^{\alpha}$, α~3,with loss of beta–gamma spectral peaks and diminished or absent oscillations and spatiotemporal phase structure. In the awaking state, the power spectral density (PSD) showed power-law decrease in log power with log frequency at $1/f^{\alpha}$, α~2, but with peaks in the standard empirical ranges [3]. In short we are able to conclude that for the state of rest, it resembles the brown noise with its slope approximately close to -2, and for deep sleep, it decreases to the range from -3 to -4 which resembles the black noise, while for light sleep, it locates at the intermediate site of the former two, and these persuasive background activities are caused by mutual excitation among cortical neurons [4]. The following contents will introduce the method to extract the distinction with PSD.

2 Methods

We choose ten blocks of one-channel EEG signal with each block consists of five-minute waking EEG, five-minute light sleep EEG (mainly in stage II for stage I is only a transient state and is not representative enough) and five-minute deep sleep EEG. These segments of EEG signal are from the dataset which was built for sleep quality analysis. It was digitized at 250Hz and with low pass filter from 0-40Hz. The data has been preliminarily judged by the method combined with Hilbert Huang Transform (HHT) and 'R-K rules' where the HHT algorithm acts as an effective way to acquire the frequency spectrum and R-K rules as the criterion for judgment, first the frequency spectrum is calculated by HHT, then these results combined with the amplitudes of both EEG and EOG are applied into the R-K rules which would determine the specific sleeping stage of each segment [5]. According to 'R-K rules', the most prominent character of awaking status is that the EEG contains alpha activity and/or low voltage, mixed frequency activity. The light sleep contains fewer alpha activities and is characterized as the spindle waves and K-complex waves; for deep sleep it elaborates that it contains great amounts of high amplitude, slow wave activity [1].

For each block, we just divided the three five-minute signals into 300 segments separately with each segments 1 second (for the sampling frequency is 250Hz, signal for each second consist of 250 points). Then we calculated the frequency spectrum of each segment in use of FFT; hence the log frequency vs. log power figure comes out. Meanwhile, we use first order fitting to build a linear function in form of $y=b*x+c$ where the parameter 'b' represents the slope of the fitting curve and c for the intercept. (Fig.1)

In Fig.1(a), Fig.1(b), Fig.1(c) it is obvious that for deep sleep stage, the power in low frequency bands like delta is overwhelmingly stronger than that of the waking stage (one order stronger), while for the relatively higher frequency bands like alpha and beta, the waking stage contains more power than sleep stage, that is why the sleep



(a) (b) (c)

Fig. 1. The PSD of one second EEG signal (the blue curve) and the straight fitted to PSD(the red curve), this PSD is from a random one second of different status. (a) awake, (b) deep sleep and (c) light sleep.

signal approximates to black noise which is characterized by the slope below -3 and the waking signal approximates to brown noise with its slope around -2. In contrast, the light sleep has relatively strong power in lower frequency compared to that of awaking status and stronger in power of 10-16Hz than that of deep sleep, determining the slope of this stage around -2.5. This is due to the K-complex activity which is in lower band (i.e. less than 2Hz) and the spindle waves which has a higher frequency band (i.e. 10-16Hz) All those above are coherent to the description in R-K rules that in waking stage, it is mainly occupied with alpha activity for more than 50% of the whole epoch in temporal domain; in deep sleep, the delta wave with peak to peak amplitude more than 75uv dominates more than half of the EEG signal in temporal domain; in light sleep, there is less alpha activity than awaking status and dominated by spindle waves and K-complex waves. This is also the cause of the steeper slope in the PDS of deep sleep.

With the acquirement of these PSD graphs, it is now possible to extract some features; thus we decide to utilize several parameters to express the characters of each segment of EEG signal. Other than the slope and intercept is the parameter named SI, which is defined as

$$SI = \frac{\sum_{n=1}^{40} |\log_{10} p| - \sum_{n=1}^{40} |\log_{10} R|}{\sum_{n=1}^{40} |\log_{10} p|} \tag{1}$$

Where

$$\sum_{n-1}^{40} |\log_{10} R| = \left| \sum_{n=1}^{40} (\log_{10} p - \log_{10} p_e) \right| \tag{2}$$

Here $\log_{10} p_e$ is the simulated value in the fitting curve. It expressed the percentage of the total variance in the designated frequency range, the smaller this index is, the more intense the frequency ranges, and the more active the state of brain is. In addition, to express the activity of alpha band which involves the prominent character of waking state, we use the SIα, which is the value of SI specifically in the alpha band (8-13 Hz).

$$SI\alpha = \frac{\sum_{n=8}^{13} |\log_{10} p| - \sum_{n=8}^{13} |\log_{10} R|}{\sum_{n=8}^{13} |\log_{10} p|} \tag{3}$$

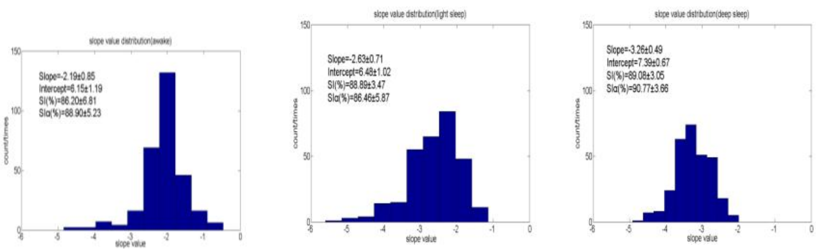
And

$$\sum_{n-8}^{13} |\log_{10} R| = |\sum_{n=8}^{13} (\log_{10} p - \log_{10} p_e)| \tag{4}$$

Also, to avoid the relatively small number of discrete point in PSD figures (totally only 40 points in log frequency vs. log power coordinate) which may not agree with law of large numbers and would create some uncertainty in calculation, it is necessary to interpolate additional points into the PSD curves. We just use spline as the way to realize the interpolation, more than 1600 points for each function are interpolated into the PSD and the fitting curve with the step as 0.001.

3 Results

The 300 segments vided in each five-minute EEG signal make it necessary to do some statistical works especially for the slope which represents the typical distinction among deep sleep, awaking status and light sleep. (Fig.2)



(a) (b) (c)

Fig. 2. Hisrograms of the slopes of PSD from human EEG (a) awake, (b) deep sleep, and (c) light sleep

The histogram in Fig.2 (a) indicates the slope near -2 and resembles brown noise. In addition, there is the tail downside towards the slope of -5. These sporadic deviations show the tendency from brown noise to black noise and the unsteady state of the waking stage. That means in this block, the waking stage goes unstable compared to deep sleep. The distribution of Fig.2 (b) appears similar to symmetry distribution, with the average slope between -3 and -4, which resembles the black noise. In Fig.2 (c), the average value of slopes is around -2.5 which goes in the middle of the waking stage and deep sleep stage with a tail towards lower value, this is because of the random occurrence of K- complex waves which has peak to peak amplitude more than 100uv, and together with the fluctuation of spindle waves in 10-16 Hz, it appears to be lower in SI and SI α.

In sum, the results are detailed in Table 1 Table 2 and Table 3, those assert that the slope of waking stage is around -2 and for deep sleep, it descends to below -3 with higher value for intercept, the slope of light sleep is in medial. Meanwhile, it also states that no matter for SI or for SIα, EEG in awake and rest is a little bit smaller than that of deep sleep for around two percentiles which means the waking EEG fluctuates more actively than sleep EEG, both in the alpha band or in the overall frequency. While for light sleep these two parameters are often lower maybe due to the fluctuation in both lower and higher frequency bands.

Table 1. The specific details for waking EEG

	Deep sleep (average±SD)			
Index / No	**SI (%)**	**SIα (%)**	**Slope**	**Intercept**
1	86.96±5.00	89.15±4.24	-3.26±0.59	7.23±0.83
2	87.25±3.65	90.04±3.23	-3.55±0.44	7.35±0.58
3	87.28±4.60	89.98±3.90	-3.32±0.60	7.58±0.82
4	88.40±4.26	90.35±3.64	-3.43±0.50	7.65±0.71
5	88.26±4.03	89.90±3.79	-3.53±0.50	7.69±0.72
6	89.30±3.15	90.93±2.90	-3.47±0.47	7.58±0.64
7	88.59±3.41	90.20±2.92	-3.42±0.48	7.64±0.65
8	89.08±3.05	90.77±3.66	-3.26±0.49	7.39±0.67
9	87.30±3.86	90.15±3.43	-3.67±0.51	7.85±0.70
10	87.94±3.96	90.08±3.45	-3.29±0.40	7.06±0.53

Table 2. The specific details for sleep EEG

	Wake (average±SD)			
Index / No	**SI (%)**	**SIα (%)**	**Slope**	**Intercept**
1	85.69±7.02	87.46±6.46	-1.64±0.78	5.35±1.12
2	86.82±5.92	89.05±5.17	-1.87±0.89	5.47±1.42
3	86.74±5.87	89.02±4.90	-1.82±0.84	5.82±1.12
4	86.38±7.03	89.02±6.06	-1.51±1.34	5.60±2.03
5	86.78±5.05	89.02±4.90	-1.61±0.63	5.55±0.96
6	86.71±5.83	87.82±5.43	-2.17±0.76	6.19±0.99
7	86.71±5.64	88.77±4.70	-2.05±0.86	6.11±1.14
8	86.20±6.81	88.90±5.23	-2.19±0.85	6.15±1.19
9	87.82±4.30	89.50±3.78	-2.25±0.50	6.11±0.69
10	86.38±8.16	88.54±8.05	-1.83±1.67	5.77±2.64

Table 3. The specific details for sleep EEG

	Light sleep (average±SD)			
Index / No	SI (%)	SIα (%)	Slope	Intercept
1	82.91±8.98	86.85±6.45	-3.15±1.22	7.21±1.78
2	84.67±6.15	88.96±4.69	-3.12±0.75	7.01±1.08
3	82.48±10.45	86.14±8.20	-3.08±1.40	7.50±2.05
4	83.02±10.80	85.79±8.64	-3.09±1.42	7.46±2.07
5	84.83±8.65	87.70±6.62	-3.02±1.17	7.25±1.69
6	86.76±5.06	89.28±4.12	-2.58±0.65	6.61±0.92
7	85.67±6.93	88.88±4.36	-2.86±0.81	6.90±1.13
8	86.46±5.87	88.89±3.47	-2.63±0.71	6.48±1.02
9	82.72±7.32	88.10±4.79	-3.40±0.90	7.50±1.30
10	87.02±5.47	89.75±4.28	-2.44±0.59	6.38±6.38

We also notice that the standard deviation in deep sleep is usually much smaller than those in the waking status with rare exceptions. We induce that it could also demonstrate that in deep sleep, the brain activity is more stable than waking periods. Another reason why the slope of waking status deviates a bit from the theoretical value -2 is due to the muscle activity (i.e. EMG) mingled into the waking EEG and forced the slopes closer to pink noise which involves higher frequency bands.

3 Discussion

Based on the power spectral density, we may find the regular patterns that for waking EEG, it is similar as brown noise, and for deep sleep EEG it is closer to black noise whose slope is much steeper, but for light sleep it is in the medial of those two; and the difference in SI and histograms shows the relatively unstable nature of waking EEG and light sleep with more fluctuations and sporadic deviations. The lower value of SIα in waking stage and light sleep just corresponds to the R-K rules that the alpha activity usually occurs in Stage W and spindle occurs in light sleep.

Hence we can conclude the radical methods in PSD based sleep stage classification, from higher to lower in absolute value, it is deep sleep, light sleep and awaking status for the value of slope; deep sleep, awaking status and light sleep for the value of SI and SIα; deep sleep, light sleep and awaking status for value of intercept. Compared to the traditional computer based time-frequency analysis, the method of PSD has its distinctive advantages. Unlike the time-frequency analysis, this method would no longer be restricted by the specific details of R-K rules, which means the distinctive difference between slopes, intercepts and SI would help to overcome the fuzzy boundary between sleep stages. Additionally, this method could be utilized for different individuals without changing the parameter of the algorithm for it is adaptive to different subjects where the comparison would occur only in the same platforms; unlike neural networks, there is no need to do any training works in advance to adjust the specific parameters and inner configurations. Accordingly, the method of PSD is also the allusion of the mechanism of human's brain, not only for its general condition of stability but also for transition of background noise. It is probable to say that this approach is another perspective to express the brain activity described in R-K rules and an effective way to realize sleep stage classification.

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