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·Original Article·

An ensemble with the Chinese pentatonic scale using electroencephalogram from both hemispheres

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ABSTRACT

To listen to brain activity as a piece of music, we previously proposed scale-free brainwave music (SFBM) technology, which translated the scalp electroencephalogram (EEG) into musical notes according to the power law of both the EEG and music. In this study, the methodology was further extended to ensemble music on two channels from the two hemispheres. EEG data from two channels symmetrically located on the left and right hemispheres were translated into MIDI sequences by SFBM, and the EEG parameters modulated the pitch, duration and volume of each note. Then, the two sequences were filtered into an ensemble with two voices: the pentatonic scale (traditional Chinese music) or the heptatonic scale (standard Western music). We demonstrated differences in harmony between the two scales generated at different sleep stages, with the pentatonic scale being more harmonious. The harmony intervals of this brain ensemble at various sleep stages followed the power law. Compared with the heptatonic scale, it was easier to distinguish the different stages using the pentatonic scale. These results suggested that the hemispheric ensemble can represent brain activity by variations in pitch, tempo and harmony. The ensemble with the pentatonic scale sounds more consonant, and partially reflects the relations of the two hemispheres. This can be used to distinguish the different states of brain activity and provide a new perspective on EEG analysis.

Keywords: electroencephalogram; music; power law; ensemble; Chinese pentatonic scale

INTRODUCTION

The electroencephalogram (EEG) has been extensively used in recent years to monitor brain activity. Normally, EEG data are presented visually. Here, we attempted to provide a new means of representing the EEG information by listening to the brain *via* the auditory pathway. This "listening" strategy may provide a more sensitive way to detect subtle variations in the amplitude and frequency of the EEG that might otherwise be ignored by conventional EEG techniques.

There is a long history of trying to "hear" hidden brain activity in a non-invasive scalp EEG. The earliest attempt to translate brainwaves into music was made in 1934[1]. A "Music for Solo Performer" was presented in 1965[2], followed by other similar music pieces. In the 1990s, several music-generating rules were created by digital filtering or coherent analysis of the EEG[3]. However, in these early works, the mapping rules were direct and arbitrary.

A breakthrough occurred in 2002[4], when various new strategies for converting the EEG into audible sounds were proposed and many artificial sound synthesizers were used for display. In recent years, two main categories of brainwave music systems based on a hierarchy of the features extracted for music generation have emerged: "EEG sonification" and the "Brain-Computer Music Interface".

EEG sonification sets out to translate a few EEG parameters into the characteristic parameters of music[2,5,6], or to use specific events as triggers for the beginning of tones or other sound events. Usually, the transformation is based on subjectively-defined translation rules[5,7], except for the scale-free brainwave music (SFBM) technology, which is based on the power law of both EEG and music[6,8]. The second category is musical application of the Brain Computer Interface (BCI)[7,9,10], where induced EEG changes are used to trigger pre-defined musical events.

The EEG data are recorded from electrodes over different regions of the brain. How to represent the important temporal and spatial features in the music or audios is the core of a music generation strategy. Reasonable methods include choosing one or several channels of interest, or recruiting all the channels to generate the music. The advantages of using one-channel data are that the translation is direct and faithfully reflects the features of the waves, but the spatial information might be ignored. Therefore, multi-channel methods have received much attention in recent years.

The most obvious approach to obtaining music from multi-channel EEG is to simply put together the melodies from each channel[11], which may result in a cacophony of dissonant sounds hard to identify. Furthermore, the spatial information of EEG channels must be taken into account[5,7]. For example, the data from the left and right hemispheres could be phonated separately in the left and right speakers. Usually, specific electrodes are chosen according to the corresponding tasks, and a pair of symmetrical electrodes is commonly selected for monitoring the left- and right-hemispheric brain activity[5]. In a BCI musical application, the spatial features are important for mental pattern recognition. Thus, almost all channels have to be used for feature extraction.

The music from EEG is atonal in most parameter-mapping methods. While the music generated by algorithms may have a tonality, this is just a subjective choice. Here, we proposed a method that included a scale filter. The sequences of atonal notes were filtered to become tonal music, which is likely to be easier to understand.

In this work, our previous SFBM technology was extended to ensemble music of two channels from the two hemispheres, and the pentatonic scale (5 notes/octave; commonly used in traditional, especially Chinese, music) and the heptatonic scale (7 notes/octave; commonly used today) were compared for their musical effects. To evaluate the attempt to convey multi-channel EEGs in an auditory musical sequence in real time, a few segments of sleep EEG were converted into musical pieces.

PARTICIPANTS AND METHODS

Initial music sequences were generated from two EEG channels from the two hemispheres according to scale-free rules[6], involving mapping EEG amplitude to note pitch, EEG energy to volume, and period of local EEG events to duration. Then the two melodies were modulated according to either the pentatonic or the heptatonic scale. EEG data from different sleep stages were included. All the data processing was conducted with Matlab 7.0.

Data Acquisition and Preprocessing

For sleep EEG data acquisition, two physically and mentally healthy male participants (25 and 23 years old, right-handed) were selected. The signals were recorded on a 32-channel NeuroScan system at a sampling rate of 250 Hz and were band-pass filtered from 0.5 Hz to 40 Hz. The EEG recordings were conducted according to the principles expressed in the Declaration of Helsinki, and were approved by the Institutional Review Board of the University of Electronic Science and Technology of China. The subjects provided written informed consent for the collection of samples and subsequent analyses. To allow adaptation to the environment, the participants slept wearing the electrode cap for one night before the data acquisition for music generation.

After the recordings, standard EEG pre-processing (artifact rejection and band-pass filtering) was used. Based on the Rechtschaffen-Kales method[12], the sleep stages were identified by visual inspection[13], and then artifact-free data segments lasting 60 s during rapid-eye-movement sleep (REM) and slow-wave sleep (SWS) were chosen separately. The data were re-referenced to infinity with

REST software[14,15]. Besides, white noise was generated by computer to create musical pieces as a control for EEG and for statistical comparison.

Channel Selection

Multi-channel EEGs contain abundant brain information. The sonification strategy in this work concerned the relations of the two hemispheres. Thus, channels located symmetrically on the left and right hemispheres were selected for music generation (e.g., Fp1-Fp2 and F3-F4). The data from the left and right hemispheres were sonified in the left and right channels of the stereo. All the symmetrical electrode pairs on the cap were used for music generation: FP1-FP2, F3-F4, F7-F8, FC1-FC2, FC5-FC6, C3-C4, T5-T6, T3-T4, CP3-CP4, PC5-PC6, P3-P4, and O1-O2. Analyses were based on all these pairs.

Generation of Single-channel Brain Music

The sonification strategy for a single channel is an important stage for music generation. A musical note has four essential parameters: timbre, duration, pitch, and intensity. In this study, the timbre of the Chinese Guqin (seven-stringed instrument of the zither family) was used, and the duration, pitch and intensity of a note were obtained respectively from an EEG event period, the wave amplitude and the change of energy.

In the proposed method, an EEG "event" began when the wave crossed the zero line from negative to positive and ended at the third such crossing. Thus, the duration of an EEG event modulated the duration of a note.

The EEG amplitudes were translated into pitch. Here, we defined the mapping rule from EEG amplitude to pitch according to the scale-free rule of both EEG and music[6].

Finally, the EEG power was used to determine the intensity. Here, the intensity was proportional to the logarithm of the rate of change of the average power according to Fechner's law[16]. This definition was based on the psychological fact that stimulus information is efficiently conveyed not by a constant signal but by its change. The details of the parameter translations were presented in our previous paper[6].

Pentatonic Scale Filtering

A musical scale is a sequence of notes in ascending or descending order. Generally, the notes of a scale belong to a single key, thus easily representing part or all of a musical work, including melody and harmony. The typical heptatonic scale has seven notes, for example, the C major scale comprises the notes C, D, E, F, G, A and B. In contrast, the pentatonic scale has five notes per octave. The pentatonic scale is usually used for Chinese folk music and consists of C, D, E, G and A.

In this work, we filtered the EEG channels to melodies according to the scales, when the originally atonal music became tonal. In other words, the MIDI sequences obtained from a single channel were filtered by the pentatonic scale. The notes on the scale were retained, and the notes off the scale were modulated. The adjustment of the off-scale notes followed two rules: the nearest and the most stable. The "nearest" principle was that the off-scale note was adjusted to the nearest on-scale note, to minimally deviate from the original signal. And the "most stable" principle meant that when the off-scale note could be adjusted to either of two notes, the more stable note was chosen. In tonic music, the stability of each note is different. For example, in C major, the main note C is the most stable, the second is the dominant G, then followed by E, F, A, D, and B. The stability of notes is based on Western musical theory[17]; here, we used it for filtering with both scales. For the pentatonic scale, the sequence is C, G, E, A, D. Therefore, during the scale filtering process, C# is near C and D, and because C is more stable than D, then C# is adjusted to C and not D. Similarly, D# is adjusted to E and not D. The scale filters are shown in Fig. 1.

Heptatonic Scale Filtering

Here, we used the C-major scale, which consists of the notes C, D, E, F, G, A and B. Similarly, we filtered translated pieces of melody from an EEG channel based on the heptatonic scale, when the original atonal music became tonal. In detail, when a note in the original MIDI melody was one of the notes in the scale, it was retained; otherwise it was changed to the nearest note in the key based on the nearest and most stable principles. For instance, if a note was F# (off-scale), the pitch was changed to G (G and F are near F# and G is more stable than F) (Fig. 1).

Brain Music Generation

The MIDI sequences were modulated according to the pentatonic or the heptatonic scale, and then both melodies

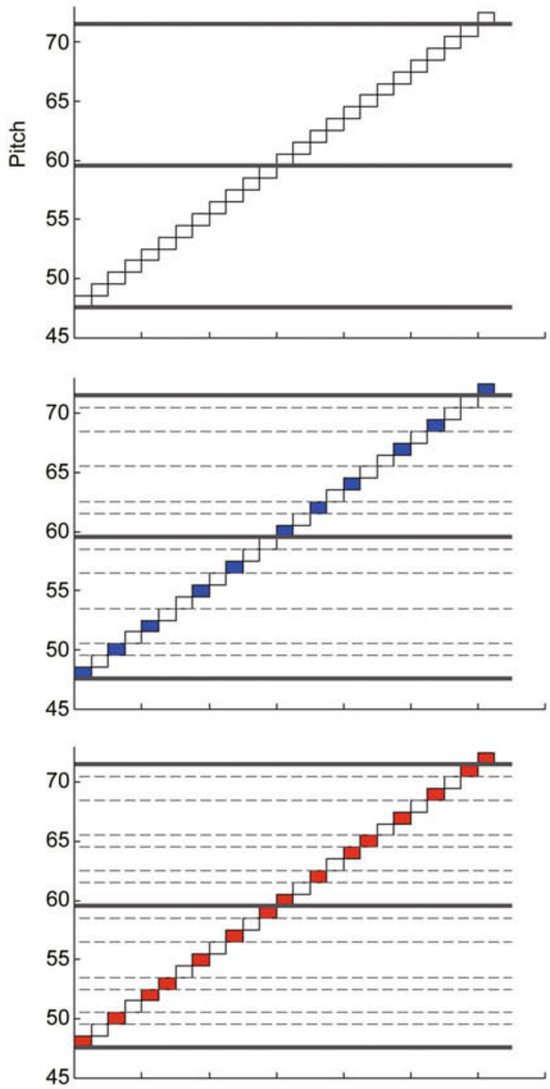

Fig. 1. The musical scale filters. The thick solid lines indicate the ends of octaves. Two octaves are taken as examples here. The first panel shows the original atonal scale, 12 notes in an octave. The second panel shows the pentatonic scale filter. The original notes between every two thin dotted lines are adjusted to the blue note. There are 5 notes in an octave. The third panel is the heptatonic scale filter. The original notes between every two thin dotted lines are adjusted to the red note. There are 7 notes in an octave.

were integrated. The pitches of the right MIDI sequences were raised one octave to ensure that the two channels could be distinguished. Thus, the signals from the left hemisphere were converted to the low voice, while those of the right to the high voice. The audios from each hemisphere were played through the left and right channels of the stereo. The music files can be converted into other format such as MP3 for evaluation or application.

Examples of the music generated from F3-F4 EEG data during REM and SWS with the pentatonic scale are shown in Fig. 2. The corresponding audio files are supplied as the Supplemental Audio S1, 60 s music from F3-F4 during REM; Audio S2, 60 s music from F3-F4 during SWS.

Definition of Interval Consonance

In an ensemble, the harmonic intervals (the distance between pitches sounding simultaneously) are very important. The consonance of such intervals is related to the frequency ratio of the notes sounding at the same time. To analyze the generated music, the harmony consonance rank (HCR) is shown in Table 1. These twelve intervals were put into four classes. The class “unisons and octaves” included the intervals unison and octave, which were the most consonant (HCR = 1); the class “perfect consonances” included the intervals perfect fifth (HCR = 2) and perfect fourth (HCR = 3); the class “imperfect consonances” consisted of intervals from HCR = 4 to 7; the class “dissonance” contained HCR = 8 to 12.

RESULTS

The EEG data during REM and SWS were used for music generation. The following analyses of the music ensembles were based on all the 12 pairs of symmetrical electrodes during REM and SWS with the pentatonic and heptatonic scales. The results were from two participants, and the values were averaged across all 12 electrodes pairs. The *t*-test was used for statistics unless otherwise stated.

Basic Attributes of Music

The generated music encompassed a wide variety of pitches. The pitch range of REM music (54.2 ± 2.4 semitones, mean ± SD) was higher than SWS music (37.8 ± 4.0 semitones) in both the pentatonic and heptatonic scales (P <0.01). Furthermore, the number of notes per minute in REM music was 209.5 ± 18.1, while that in SWS music was 78.5 ± 19.7 in both scales, so the REM music sounded faster than the SWS music (P <0.01).

Harmonic Intervals

For the pentatonic scale, the harmonic interval of REM

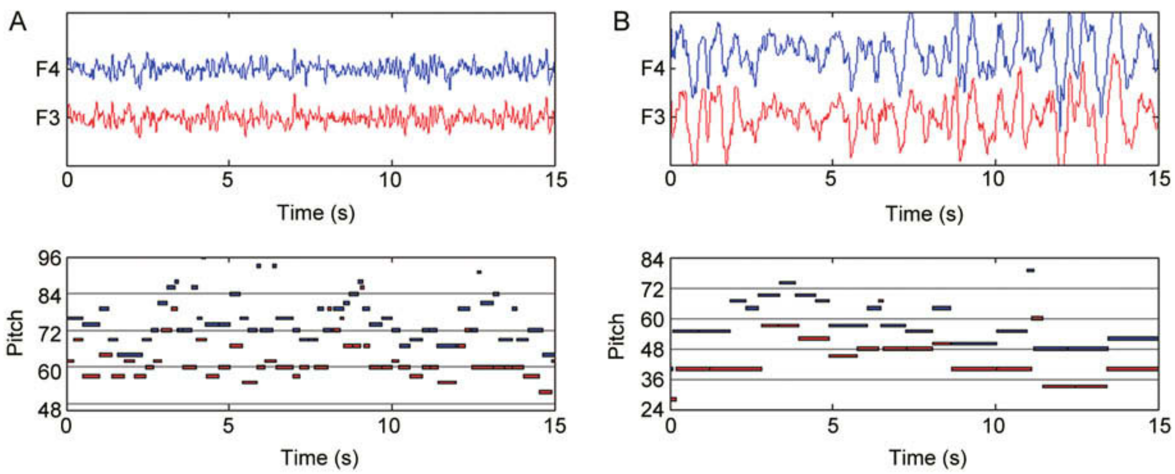

Fig. 2. EEG signals and the generated music from electrodes F3 (left hemisphere) and F4 (right hemisphere) in participant A. (A) EEG and music during REM sleep (red from F3 and blue from F4), (B) EEG and music during SWS sleep (red from F3 and blue from F4).

Table 1. Mapping rule for pitch intervals, interval names, and harmony consonance rank

Pitch interval	Interval name	Harmony consonance rank
0	Unison/octave	1
1	Minor second	11
2	Major second	8
3	Minor third	6
4	Major third	4
5	Perfect fourth	3
6	Augmented fourth /Diminished fifth	12
7	Perfect fifth	2
8	Minor sixth	7
9	Major sixth	5
10	Minor seventh	9
11	Major seventh	10

was 4.4 ± 0.3 semitones, and that of SWS was 4.1 ± 0.5 semitones. For the heptatonic scale, it was 4.7 ± 0.3 semitones of REM, and 4.5 ± 0.5 of SWS. Two-way ANOVA showed that there were significant differences between the two scales (P <0.01) and the two sleep stages (P <0.01). The harmonic intervals of REM were larger than those of SWS, indicating that during REM, the differences between the left and right hemispheres were larger. Such results are in accord with previous studies[18], and the lateralization during REM might be due to activity related to emotion and memory[19].

To compare the music of the two scales, we calculated the distribution of the four classes of interval consonance with the two scales during REM and SWS (Fig. 3). We found that in the "dissonance" class, the pentatonic scale was significantly lower than the heptatonic scale (P < 0.05) during both REM and SWS. And across the three "consonance" classes, excluding the "perfect consonances" class for SWS, the pentatonic scale scored higher than the heptatonic scale (P <0.05). These results indicated that the music with the pentatonic scale sounded more harmonious than did the heptatonic scale.

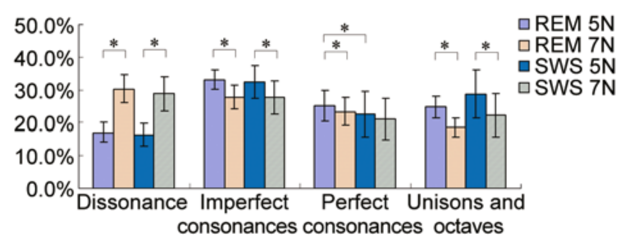

Fig. 3. Distribution of interval consonance of REM and SWS music for all 12 electrodes pairs from two participants with the pentatonic scale (five notes, 5N) and the heptatonic scale (seven notes, 7N).

Besides, in the "perfect consonances" class, we found significant differences between REM and SWS with the pentatonic scale (P <0.05). But for the heptatonic scale, REM and SWS showed no differences in any consonance classes. Such results suggested that the pentatonic scale might more easily distinguish mental states.

Music of White Noise

We also analyzed the music generated from white noise following the same processing as the EEG data. The EEG music pieces were more consonant than white noise music (P <0.05) for both scales. This indicated that the harmonic features of the brain activity were represented in the generated music, and showed better musical potential. Furthermore, the noise music of the pentatonic scale differed from that of the heptatonic scale (P <0.01), indicating that the former made more harmonious music than the latter.

Power Law of the Brain Ensembles

We analyzed the power law distribution of the brain ensembles. The pitch distribution followed the power law. The mean values of all the symmetrical electrode pairs during REM were −1.50 ± 0.16 with the pentatonic scale, and −1.38 ± 0.13 with the heptatonic scale. The power law exponent during SWS was −1.14 ± 0.08 with the pentatonic scale, and −1.04 ± 0.07 with the heptatonic scale. The differences between the two scales and between the sleep stages were all significant (P <0.05). These results are consistent with previous research[6].

In this work, we were concerned with the distribution of interval consonance in the ensemble. We calculated the number of occurrences of intervals, and then these numbers were put in descending order in logarithmic coordinates. The slope of the fit line of these points gave the power law exponent. The exponent of REM with the pentatonic scale was −1.34 ± 0.08, and with the heptatonic scale was −1.10 ± 0.10. During SWS, it was −1.00 ± 0.11 with the pentatonic scale, and −0.94 ± 0.15 with the heptatonic scale. With both scales, the exponents of REM differed from those in SWS (P <0.01). As an example, the details of the power law distribution of harmony obtained from channels F3 and F4 of participant A are shown in Fig. 4. Then we considered the differences between the two sleep stages with the different scale filters, and the results showed

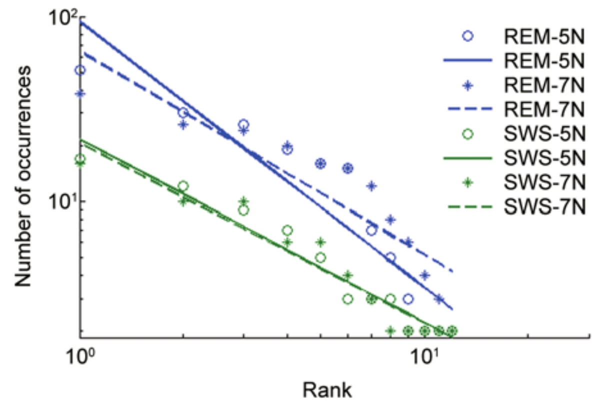

Fig. 4. Power law of the interval consonance distribution of the brain ensemble from F3-F4 of participant A. The slope of the REM line was −1.44 for the pentatonic scale (five notes, 5N), and −1.10 for the heptatonic scale (seven notes, 7N). The slope of the SWS line was −0.99 for the pentatonic scale, and −0.97 for the heptatonic scale.

that the differences in the power law exponents for the pentatonic scale were larger for the heptatonic scale (P < 0.01). Therefore, the differences in EEG at sleep stages were amplified by the pentatonic scale filter.

DISCUSSION

It is known that people are more accustomed to tonal than atonal music, especially in an ensemble, because a tonal scale makes the music easier to understand. In an atonal ensemble, too many inconsonant intervals sound messy. Usually, useful EEG information is obtained after the noise is filtered out. Here the (Chinese) pentatonic scale was a kind of musical filter and modified partial unusual intervals of pitch so that a reasonable musical consonance was conserved.

Compared to the (Western) heptatonic scale, the pentatonic scale showed stronger potential for listening to and discriminating brain activity: the intervals sounded more consonant and made the differences between brain stages more perceptible. The reason the pentatonic scale sounds more harmonious might be that 5 notes in an octave lead to the reduction of dissonant intervals in the music. In terms of distinguishing REM from SWS, the "perfect consonances" class was significantly different only for the pentatonic scale, where more perfect fifth or fourth intervals were generated. The perfect fifth and fourth are primary intervals in a tonic scale; therefore differences in them impress the listener. Furthermore, there were corresponding power law exponents of interval consonance at different sleep stages, and these variations in the pentatonic scale were larger than those in the heptatonic scale.

The brainwave music derived by our EEG-music mapping rules suggests that the activities of the left and right hemispheres can be represented by ensemble music from two-channel EEG signals, and a (Chinese) pentatonic scale filter can make the ensemble music sound consonant. The details of EEG parameters, such as amplitude, period, and lateralization were revealed. The proposed method can provide comfortable and long-term observation of EEG. It is a new aspect of perceiving brain activity and may be useful in clinical monitoring and biofeedback.

SUPPLEMENTAL DATA

Supplemental data include two audios of music from F3-F4 EEG during REM and SWS sleep respectively with the pentatonic scale, and can be found online at http://www.neurosci.cn/epData.asp?id=85.

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REFERENCES

[1] Adrian ED, Matthews BHC. The Berger rhythm: potential changes from the occipital lobes in man. Brain 1934, 57(4): 355.

[2] Rosenboom D. Biofeedback and the Arts, Results of Early Experiments. Vancouver: Aesthetic Research Centre of Canada, 1976: 27–109.

[3] Rosenboom D. Extended Musical Interface with the Human Nervous System: Assessment and Prospectus. San Francisco: International Society for the Arts, Sciences and Technology, 1997: 26–101.

[4] Hermann T. Sonification for exploratory data analysis. Bielefeld: Bielefeld University, 2002: 31–44.

[5] Hinterberger T, Baier G. Parametric orchestral sonification of EEG in real time. IEEE Multimedia 2005, 12(2): 70–79.

[6] Wu D, Li C, Yao D. Scale-free music of the brain. PLoS One 2009, 4(6): e5915.

[7] Baier G, Hermann T, Stephani U. Event-based sonification of EEG rhythms in real time. Clin Neurophysiol 2007, 118(6): 1377–1386.

[8] Lu J, Wu D, Yang H, Luo C, Li C, Yao D. Scale-free brainwave music from simultaneously EEG and fMRI recordings. PLoS One 2012, 7(11): e49773

[9] Wu D, Li C, Yin Y, Zhou C, Yao D. Music composition from the brain signal: representing the mental state by music. Comput Intell Neurosci 2010. Doi: 10.1155/2010/267671.

[10] Miranda ER. Plymouth brain-computer music interfacing project: from EEG audio mixers to composition informed by cognitive neuroscience. Int J Arts Technol 2010, 3(2): 154–176.

[11] Vialatte F, Cichocki A. Sparse bump sonification: a new tool for multichannel eeg diagnosis of mental disorders; application to the detection of the early stage of Alzheimer's disease. Neural Inf Process 2006, 4234: 92–101.

[12] Rechtschaffen A, Kales A. A Manual of Standardized Terminology, Techniques and Scoring System for Sleep Stages of Human Subjects. Los Angeles: Brain Information Service, 1968: 1–57.

[13] Fang G, Xia Y, Zhang C, Liu T, Yao D. Optimized single electroencephalogram channel sleep staging in rats. Lab Anim 2010, 44(4): 312–322.

[14] Yao D. A method to standardize a reference of scalp EEG recordings to a point at infinity. Physiol Meas 2001, 22: 693.

[15] Qin Y, Xu P, Yao D. A comparative study of different references for EEG default mode network: The use of the infinity reference. Clin Neurophysiol 2010, 121(12): 1981–1991.

[16] Fechner GT. Elements of psychophysics. In: Howes DH, Boring EG (Eds.). Elements of Psychophysics (trans. Adler HE). New York: Holt, Rinehart and Winston, 1966: 113–170.

[17] Schoenberg A. Theory of Harmony. Ewing: University of California Press, 1983: 18–286.

[18] Armitage R. The distribution of EEG frequencies in REM and NREM sleep stages in healthy young adults. Sleep 1995, 18(5): 334–341.

[19] Flo E, Steine I, Blagstad T, Gronli J, Pallesen S, Portas CM. Transient changes in frontal alpha asymmetry as a measure of emotional and physical distress during sleep. Brain Res 2011, 1367: 234–249.