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Quantifying and Analyzing Brainwave Electroencephalography with Welch's Method

Che-An Chiu,[1] Ming-Chi Lu,[1*] Yan-Lin Zhong,[1]
Tang-Yi Tsai,[2] Chia-Ju Liu,[2] and Ming-Chung Ho[1]

[1]Department of Physics, National Kaohsiung Normal University,
No. 62, Shenjhong Rd., Yanchao District, Kaohsiung City 824, Taiwan
[2]Graduate Institute of Science Education & Environmental Education, National Kaohsiung Normal University,
No. 62, Shenjhong Rd., Yanchao District, Kaohsiung City 824, Taiwan

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Brainwave signals are analyzed in the nonlinear analysis field and are often studied by electroencephalography (EEG) using brain sensors. Although various frequency bands of brainwaves, such as α, β, and θ brainwaves, can be filtered out from multi-frequency brainwave signals, most modern medicine only interprets the meaning of the signals superficially and rarely conducts an in-depth quantitative analysis of brainwave data. In this study, we selected healthy adults to experimentally analyze their sleep in three stages: before sleep, during sleep, and awakening after sleep, and we observed the energy changes of the brainwaves in these three different periods. We used Welch's method to quantify the EEG data for analysis. It is generally believed that the brainwave energy is lower when asleep than when awake. However, our experimental results show that not all brainwave energy is higher when awake than when asleep, that is, the brainwave energy in certain bands at the frontal cortex location Fz, the parietal cortex location Pz, and the central cortical location Cz is higher when asleep than when awake. In the future, this method may be extended by applying brain sensors to people with insomnia, Alzheimer's disease, amnesia, anxiety, emotional disorders, and so forth.

1. Introduction

Sleep periods are roughly divided into the rapid eye movement period (REM) and the non-rapid eye movement period (NREM).(1) The sleep process is divided into three stages, namely, the wide awake stage before sleep, the sleep stage, and the awakening stage after sleep. The second stage of sleep is divided into three periods, namely, falling asleep, light sleep, and deep sleep.(2) Most sleep studies only focus on the phase during sleep, which is calculated from NREM, and do not include REM before sleep and the awakening period after sleep. Such research is limited to studying the situation during sleep entry and does not include the causes and effects of overall sleep. According to the findings of Tsunematsu *et al.*, brain energy expenditure is highest during REM when gamma activity increases.(3) The gamma brainwave is

*Corresponding author: e-mail: tea0075@gmail.com
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therefore an important factor in comparing the energy changes during the wide awake, sleep, and awakening stages.

Electroencephalography (EEG) remains a dominant technique for investigating the brain, even though nearly a hundred years has passed since its discovery in 1929.(4) Although modern brainwave examinations mostly rely on the frequency and amplitude to interpret the representations of the brain, superficially interpreting the changes in frequency and amplitude cannot provide a deeper understanding of brainwaves. Therefore, EEG has not played a significant role in clinical medical applications. Most studies on EEG sleep have only focused on the sleep stage, with little analysis of the wide awake stage before sleep and the awakening stage after sleep. Changes in brainwaves are very rapid. When people are awake, close their eyes, open their eyes, or are instantly affected by variation in the external environment, there are obvious changes in brainwaves. Brainwaves are multi-frequency waves and can be divided into α, β, δ, and θ brainwaves with different frequencies.(5) Generally, an α brainwave can be detected when the concentration is reduced, the mood is relaxed, or the eyes are closed. The β brainwave is associated with consciousness and can be detected when people are concentrating on thinking, are reasoning, or are feeling tense. The θ brainwave is a subconscious wave that can be detected during sleep. The δ brainwave is an unconscious brainwave necessary for restorative sleep. The combination of α, β, δ, and θ brainwaves can reflect human behavior and learning performance. Therefore, a complete brainwave sleep study should include the collection of data at three stages, namely, before sleep, during sleep, and waking after sleep, so as to enable a complete data analysis and comparison.

In addition, brainwave studies must explore different cerebral cortex locations, including the frontal, parietal, occipital, and temporal lobes. Each lobe is a part of the cortices connected spatially and has a distinct primary function, such as the frontal lobe for higher cognitive function, the temporal lobe for auditory function, the occipital lobe for visual processing, and the parietal lobe for the integration of visual and somatosensory information.

In recent years, owing to the widespread use of nonlinear theory, research combining brainwave signals with nonlinear theory has been performed.(6,7) Typically, brainwave signals are processed by the Fourier transform, which has the advantage of a higher calculation speed, but the frequency resolution is relatively low. In this study, Welch's method, which is an improved spectrum conversion tool for analyzing the spectrum of brainwaves more finely and is able to optimize the experimental results, is used to deal with brainwave signals. Our experimental finding differs from the general perception of brainwave energy, that is, the energy of certain brainwaves is found to be higher at certain cortical locations when asleep than when wide awake; in other words, certain brainwaves are still performing tasks during sleep. Our experimental results are expected to help improve the sensitivity and effectiveness of brain sensors.

2. Materials and Method

2.1 Materials

2.1.1 Subjects

The main purpose of this study was to analyze signals measured from EEG and to use Welch's method to obtain more in-depth information. In our experiment, we selected a total of 16 healthy adults (nine males and seven females, all right-handed) as subjects. All gave written informed consent and met the following conditions prior to testing: (1) not taking any prescription medications, (2) no history of epilepsy, (3) not been diagnosed with any sleep disturbance, and (4) no hearing impairment. This study complied with the Declaration of Helsinki and was approved by the Ethics Committee of National Kaohsiung Normal University.

2.1.2 Music experiment

In this study, suitable sleep music was selected for the experiment, and the sleep music was played through a pair of closed earphones to prevent external noise interference. The experiment had a duration of 18 min and was divided into three stages: (I) first rest quietly for 3 min (awake stage), (II) then listen to experimental music for 12 min (sleep stage), (III) finally rest quietly again for 3 min (awakening stage). EEG signals were collected over 18 min for analysis by power spectral density (PSD).

2.2 Method: PSD with Welch's method

Welch's method is used to estimate the power of a signal at different frequencies. In this study, the method is based on the period spectrum estimation, which is the result of transforming the signal from the time domain to the frequency domain. It has the advantage of reducing noise in the estimated power spectrum. The calculation process of Welch's method is to cut a time series into M parts with a length of N points and multiply each part by a window function that is not zero only for a period of time.

$$x_m(n) = w(n)x(n + mR),\ n = 0, 1, \ldots, N - 1, m = 0, 1, \ldots, M - 1 \tag{1}$$

$w(n)$ is the total length of the window function N. x_m is the mth time series after cutting. R is the time series displacement length.

The spectral estimation (PSD) of each N-point time series in the mth segment is as follows:

$$P_{x_{m,M}}\left(f\right)=\frac{1}{N}\left|\sum_{n=0}^{N-1}x_m(n)e^{-\frac{j2\pi nk}{N}}\right|^2 . \tag{2}$$

Then, the PSD of the entire time series can be expressed as

$$P_w\left(f\right)=\frac{1}{M}\sum_{m=0}^{M-1}P_{x_{m,M}}\left(f\right) . \tag{3}$$

Next, the PSD in each brainwave band (α, β, θ, and so forth) at each cerebral cortex location during the wide awake stage before sleep, the sleeping stage, and the awakening stage after sleep is calculated for analysis and comparison.

3. Experimental Results

For a long time, most studies in physiology and sleep science have confirmed that the light sleep stage is much longer than the deep sleep stage, as measured by the duration of human sleep throughout the night.[8] In addition, many previous studies have shown that the energy of the brain is lower when asleep than when awake. However, we used Welch's method to analyze the cyclic alternating pattern of brain energy in REM and NREM at different sleep stages, and we filtered out the α, β, θ, and other EEG signals in the cerebral cortex locations of the frontal, parietal, occipital, and temporal lobes, then we analyzed the data and compared the energy during sleep with that during wakefulness. We found that not all brainwave bands were lower during sleep, but the energy of certain brainwave bands was higher when asleep. For example, the sleep brainwave energy in the theta and low beta (spindle) bands at the cortical locations Fz, Pz, and Cz was higher than that when awake.

In Fig. 1, red lines represent the stage that the subject is asleep, blue lines represent the stage before the subject is asleep, and green lines represent the stage after the subject is awakened from sleep. Moreover, Fz belongs to the cerebral cortex location of the frontal lobe, Pz belongs to the cerebral cortex location of the parietal lobe, and Cz belongs to the cerebral cortex location of the central lobe. From Fig. 1, it can be seen that the red lines (representing sleep) in the theta and low beta bands at the Pz, Cz, and Fz locations are obviously higher than the blue lines (wide awake) and green lines (awakening).

In addition, we also found specific phenomena of gamma activity during REM of sleep and during awakening, as shown in Fig. 2.

According to the results of this study, the brainwave energy at about 60 Hz in the gamma band at the cortical location Fz was slightly higher when asleep than when awake after sleep, as shown in Fig. 2(a). In addition, regardless of the cortical location (Fz, Pz, or Cz), the brainwave energy of the entire gamma band is slightly higher when asleep than when wide awake before sleep.

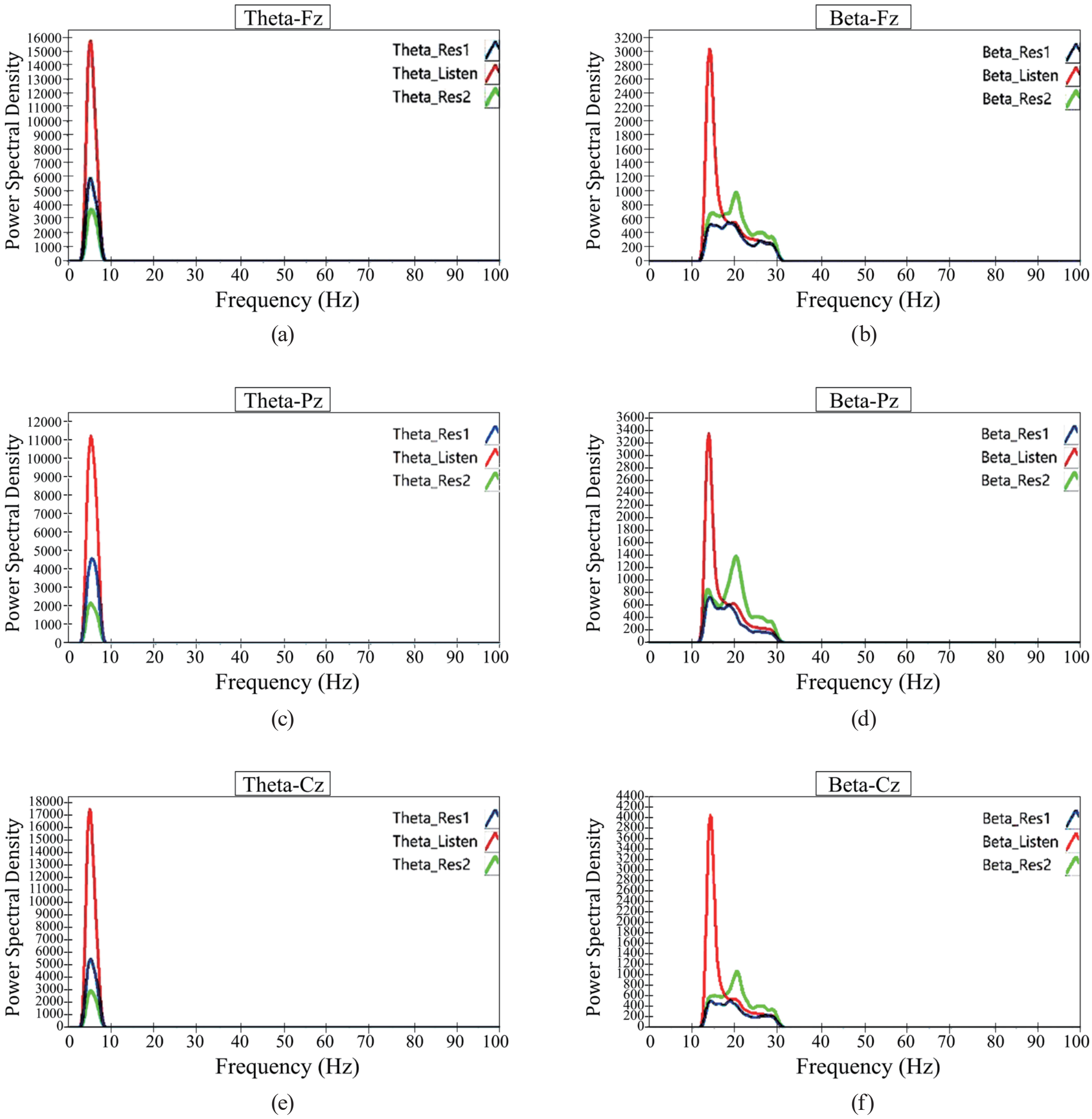

Fig. 1. (Color online) Plots of PSD in theta band at (a) Fz, (c) Pz, and (e) Cz cortical locations and in beta band at (b) Fz, (d) Pz, and (f) Cz cortical locations. Blue lines present the wide awake period before listening to experimental music, red lines present the sleep period when listening to experimental music, and green lines present the awakening period after listening to experimental music.

4. Discussion

The theta brainwave is a subconscious brainwave that appears in states of meditation and deep relaxation. The sleep period in our experiment was very close to this state; thus, it should be possible to observe the activity of the theta brainwave during this period. Our experimental results were as expected; the brainwave energy in the theta band at the cortical locations Fz, Pz, and Cz was higher when asleep than when awake, as shown in Figs. 1(a), 1(c), and 1(e). As Sih

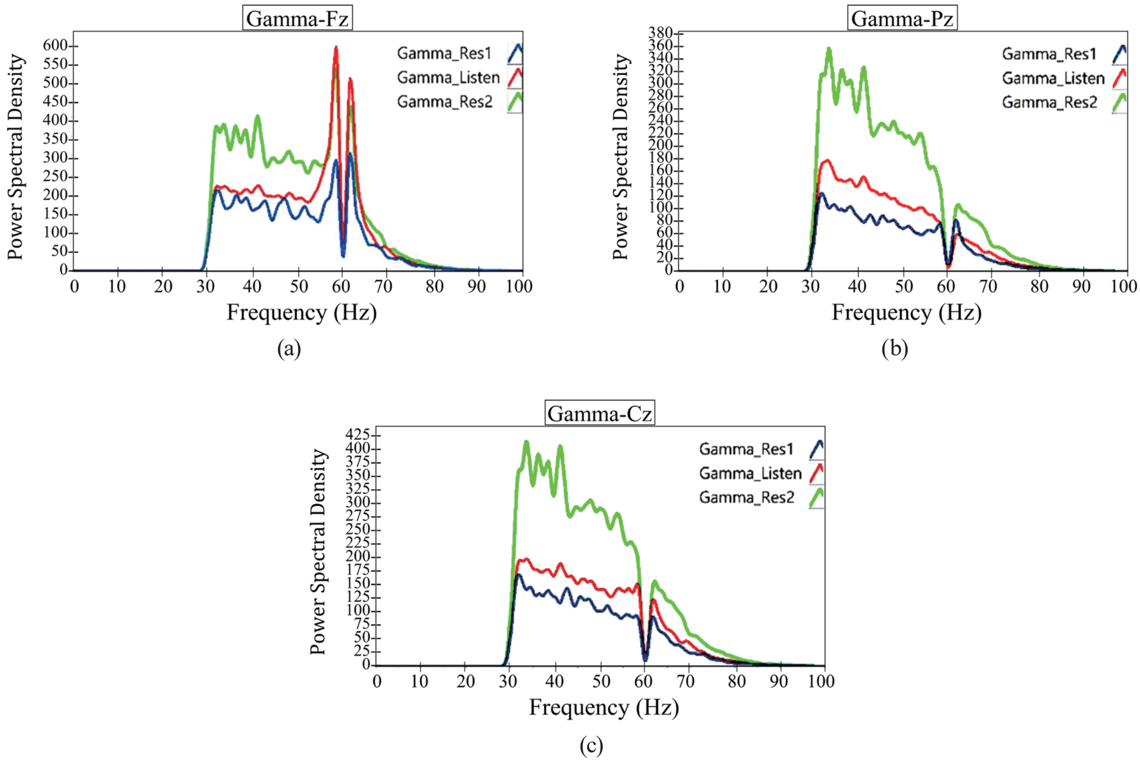

Fig. 2. (Color online) Plots of PSD in gamma band at (a) Fz, (b) Pz, and (c) Cz cortical locations. Blue lines present the wide awake period before listening to experimental music, red lines present the sleep period when listening to experimental music, and green lines present the awakening period after listening to experimental music.

and Tang explained, in NREM state N2, when the theta brainwave dominates, it becomes more difficult to awaken the sleeper.(9,10) When the theta brainwave dominates, the energy in the theta band may be higher when asleep than when awake.

Secondly, our experimental results revealed that the brainwave energy in the low beta band at the cortical locations Fz, Pz, and Cz at around 14 Hz was higher when asleep than when awake, as shown in Figs. 1(b), 1(d), and 1(f). This is because the frequency band around 14 Hz belongs to the spindle wave, which is the brainwave that occurs during sleep; thus, the brainwave energy is higher when asleep than when awake.(11,12)

In addition, Valderrama *et al.* proposed that gamma oscillations can occur spontaneously during slow-wave sleep (SWS), and this gamma brainwave appears when someone experiences reasonably high brain activity or enters deep sleep.(13) According to BuzsÁk,(14) bursts of the gamma wave can occur in both high-frequency bands (60–120 Hz) and low-frequency bands (30–50 Hz), which confirms that even when the brain enters sleep, the gamma wave can be activated, and this phenomenon of gamma activation has a specific meaning in physiology. However, the neuronal mechanisms underlying high gamma activity and its unique response properties in humans are still largely unknown.(15) At present, most physiological research supports the hypothesis that gamma waves between 30 and 120 Hz can promote communication between conscious neurons in a meaningful way.(16) Many studies on EEG analysis have also shown that gamma activity is related to a variety of cognitive functions, including the association between memory content and neurons.(17,18) Therefore, although human memory is best when awake, this is not always the case. Sometimes, certain items that are not remembered when awake are recalled by the brain when asleep.(19) Howard *et al.* showed that gamma oscillations can help retain information longer.(20)

It was revealed from Fig. 2 that the gamma brainwave was activated during and after listening to the experimental music(21) and that the brainwave energy at the cortical location Fz during sleep was slightly higher at around 60 Hz. The cortical location Fz is located in the frontal lobe of the brain, and thinking ability is one of the main functions of this lobe. This means that even sleep can boost the functioning of brain memory.(22)

From the above, it is revealed that the activity of the brain is not static even during sleep. When a person is resting, the brain is still working, but the nature of the work is different from that when the person is awake, and the way of working is also different.(23,24) For example, the fact that people do not dream when they are awake can be used to conclude that the experimental gamma brainwave energy was higher during sleep than when awake.

5. Conclusions

The main purpose of this study was to optimize the characterization of experimental results by using Welch's method for the more refined analysis of EEG in certain frequency bands. The experimental results showed that, owing to the state of sleep relaxation, the brainwave energy in the theta and low beta bands at certain cortical locations was higher when asleep than when awake, and the gamma brainwave energy at certain cortical locations was also higher when asleep than when awake. It was found that not all brainwave energy is higher when awake than when asleep, and some brainwaves still have tasks in progress during sleep.

In this study, we analyzed the brainwaves of healthy adults. In the future, the experimental analysis can be extended to other groups such as people with insomnia, Alzheimer's disease, amnesia, anxiety, and emotional disorders, so that brain sensors can be used optimally.

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