35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

EEG Brain Mapping and Brain Connectivity Index for Subtypes Classification of Attention Deficit Hyperactivity Disorder Children During the Eye-Opened Period

Supassorn Rodrak *Student Member, IEEE* and Yodchanan Wongsawat, *Member, IEEE*

Abstract— **Attention deficit hyperactivity disorder (ADHD) is one of the most prevalent neurological disorders. It is classified by the DSM-IV into three subtypes, i.e. 1) predominately inattentive type, 2) predominately hyperactive-impulsive type, and (3) combined type. In order to make the treatment via the neurofeedback or the occupational therapy, quantitative evaluations as well as ADHD subtype classification are the important problems to be solved to enhance an alternative way to treat ADHD. Hence, in this paper, we systematically classify all of these three subtypes by the 19-channel EEG data. Three brain mapping (QEEG) techniques, i.e. absolute power of frequency bands, coherence, and phase lag, are employed to visualize each type of the ADHD. ADHD children with combined type have deficit in delta theta and alpha activity. For the inattentive type, there are excessive delta and theta absolute power in the frontal area as well as the excessive coherence in beta and high beta frequency bands. For the hyperactivity and impulsive type, the behavior is dominated by the slow wave. This information will give benefits to the psychiatrist, psychologist, neurofeedback therapist as well as the occupational therapist for quantitatively planning and analyzing the treatment.**

I. INTRODUCTION

Attention deficit hyperactivity disorder (ADHD) is the presence of a genetic biochemical disorder. It does not allow people to work to their full potential. The prevalence of ADHD in USA was reported by center for disease control and prevention to be approximately 9.5% in the children 4-17 years of age. For Thailand, it was approximately 5% of Thai population (reported by the Child and Adolescent Mental Health Rajanagarindra Institute of Thailand). According to the Diagnostic and Statistical Manual of Mental Disorders (DSM) published by the American Psychiatric Association (APA), DSM-IV distinguishes three subtypes of ADHD, i.e. 1) predominately inattention type, 2) predominately hyperactive-impulsive type, and (3) combined type. This classification is based on three groups of symptoms i.e. 1) inattention, 2) hyperactivity and 3) impulsivity. Besides the expression of symptoms, quantitative evaluation via the brain function still needs to be developed for the systematic way to diagnose and evaluate the ADHD.

Research is supported in part by National Research University (NRU) Funding of Mahidol University, Thailand.

Supassorn Rodrak is with the Department of Biomedical Engineering, Mahidol University, 25/25 Putttamonthon 4, Salaya, Nakornpathom 73170, Thailand (email: supassorn.rod@student.mahidol.ac.th).

Yodchanan Wongsawat is with the Department of Biomedical Engineering, Mahidol University, 25/25 Putttamonthon 4, Salaya, Nakornpathom 73170, Thailand (corresponding author, phone: 66-82-889-2138 Ext 6361; fax: 66-82-889-2138 Ext 6366; e-mail: yodchanan.won@mahidol.ac.th).

The electroencephalogram (EEG) biofeedback training (One type of neurofeedback) using live z-scores and a normative database is reported to be one of the most efficient alternative methods for treating ADHD children without using drug. This method was proposed by Thatcher [1]-[3]. By using the electroencephalogram (EEG) published database that includes more than 600 people, ages 2 to 82, live z-score training employs the brain's self-regulation for training the brain to norm. Understanding how the brain function is very important information for treating with live z-score training. If the brain dysfunction of ADHD children is early identified, it will make the high effectiveness in the training.

To consider the brain dysfunction, EEG brain mapping needs to be efficiently constructed. It is one kind of brain imaging over surface that is constructed from the multi-channel of EEG. This tool can efficiently guide the neurotherapist to the noninvasive direct treatment of the brain called neurofeedback. EEG brain mapping (or Quantitative EEG, QEEG) includes absolute power, relative power, amplitude asymmetry, coherence, phase lag, etc., over different frequency bands, i.e. delta, theta, alpha, beta, and high beta.

Barry et al. reported the difference of EEG coherence between the inattentive type and combined type when the children were in the resting state. He showed greater intrahemispheric coherence at theta band and beta band of the combined type than the inattentive type [4]. Clarke et al. compared the coherence of ADHD children with normal people in resting state condition. They found that ADHD children had excess intrahemispheric coherence at theta band and beta band. The abnormality of the interhemispheric coherence appeared in the whole brain of ADHD children at theta band [5]. The difference between QEEG of girl with combined type and girl with inattention type were reported by Dupuy. The signals of children were recorded in resting eyes-closed condition. They reported that a girl with ADHD has increased slow wave activity. Considering between two types, girls with combine type had greater right hemisphere than inattentive type at theta band [6].

In order to extent the previous works to classify all three subtypes of the ADHD simultaneously during the eye-opened period, in this paper, three QEEG techniques, i.e. absolute power of frequency bands, coherence (shared information capability between sites of brain), and phase lag (shared information speed), are considered.

II. RELIABILITY

Reliability of the QEEG is closely related with the sample sizes. Salinsky et al. reported that 20 seconds of sample gave 82% reliability. Increasing in the EEG sample sizes to 40 seconds, the reliability was up to 90% and at 60 seconds there were approximately 92% [7]. Although some QEEG is highly reliable even with relatively short sample sizes but the recommendation of most QEEG experts was at least 60 seconds of the artifact-free EEG [8], [9]. In this study the test-retest reliability was considered. The reliability value was allowed if test-retest value was greater than 90%.

III. QEEG TECHNIQUES

In this section, three QEEG techniques, i.e. absolute power of frequency bands, coherence, and phase lag, are reviewed.

A. *Absolute Power of Frequency Bands*

The amounts of absolute powers are obtained by taking the amplitude of the fast Fourier transform (FFT) based power spectrum of each EEG channel. After that topographic map via 2D spline interpolation will be applied to get the brain mapping. This amount of absolute power is also known as the quantitative EEG (QEEG). It is the amount of each frequency band of EEG at a specific location on the scalp. One way to estimate this amount is by using the parametric spectral estimation as follows

$$H(f) = \frac{\sigma^2}{\left|FFT(a(n))\right|^2}\ , \tag{1}$$

where $H(f)$ is the amount of power at any frequency (f). The power spectrum is scaled by the square of standard deviation, σ . $a(n)$ represents the autoregressive model coefficients which can be found by matching the model and the autocorrelation function.

The quantities (Q) of the signal in a given frequency band can be calculated by integrating the amount of $H(f)$ over frequency bands of interest, i.e.

$$Q = \int_{F1}^{F2} H(f)df. \tag{2}$$

The range (F_1, F_2) is the frequency range of each EEG band. In this work, we consider EEG in 5 frequency bands. That are delta (1-4 Hz), theta (4-8 Hz), alpha (8-12.5 Hz), beta (12.5-18 Hz) and high beta (18-30 Hz).

B. *Coherence*

Coherence is a measurement of a degree of similarity of the shared information among all sites of the brain. To briefly understand the coherence, we consider at the phase difference between two signals. When the phase difference between signals is constant then coherence is 1, when the phase difference between signals is random then the coherence is 0. To achieve the coherence between two time series, the first step is to compute the autospectrum of each series based on the atom of the spectrum (the sine and cosine coefficients is referred as the atoms of spectrum analysis [10]). For a signal $x(i)$, the sine and cosine coefficients are calculated by following equation,

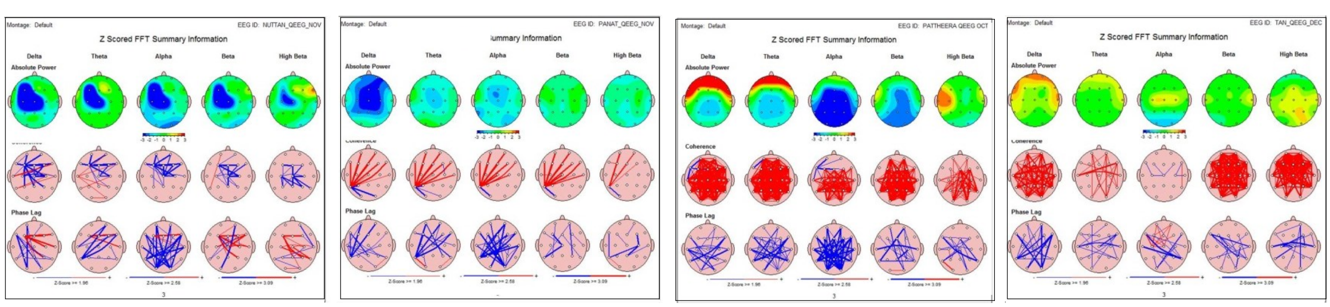
$$\text{Cosine coeffficients} \quad = \Delta t \sum_{i=1}^{N} x(i)\cos(2\pi f i \Delta t)\,, \tag{3}$$

$$\text{Sine coeffficients} \quad = \Delta t \sum_{i=1}^{N} x(i)\sin(2\pi f i \Delta t)\,, \tag{4}$$

where $x(i)$ is the signal with N points of samples, Δt is the sample interval and f is the frequency of cosine and sine basis. To compute the actual autospectrum value, we square and add the respective sine coefficients and cosine coefficients for each time series. Intuitively speaking, autospectra is the Fourier transform of the autocovariance function. Similarly, the second step is to compute the cross-spectrum of each time series from the atoms of the spectrum (Fourier transform of the cross-covariance function). The meaning of cross-spectrum is the connectivity based on the shared energy between two locations at any specific frequencies. Coherence is a normalization of cross-spectrum by the ratio of the cross-spectrum and the autospectrum of both time series. The value of coherence varies from 0 to 1.

C. *Phase Lag or Phase Difference*

Regarding the EEGs between two sites, phase lag are used to estimate the synaptic integration times [11]. In other words, phase lag indicates the speed of shared information between two sites of the brain. To compute the value of phase lag, we consider the cospectrum and quadspectrum. Cospectrum and quadspectrum can be simply calculated via the real part and imaginary part of Fourier transform of the cross covariance function, respectively. Phase lag is the ratio between the quadspectrum and cospectrum. The process on getting the Fourier transform can be simply employed the cosine and sine coefficients similar to Eqs.(3) and (4).



a b c d

Figure 1. Brain map of patient with ADHD (a) patient 1(ADHDcom), (b) patient 2 (ADHDcom), (c) patient 3 (ADHDin) and (d) patient 4 (ADHDin)

TABLE I. INFORMATION OF THE PARTICIPATED ADHD PATIENTS

Patient	Age (year)	Gender	Diagnosis	Data length (second)	Edited length (second)
1	8	M	ADHDcom	521	64
2	6	M	ADHDcom	456	73
3	15	F	ADHDin	618	82
4	8	M	ADHDin	505	64
5	8	M	ADHDhy	513	96
6	8	M	ADHDhy	483	94

M, male; F, female; ADHDcom, ADHD with predominately combined type; ADHDin, ADHD with predominately inattentive type; ADHDhy, ADHD with predominately hyperactive-impulsive type; data length, length of data that were recorded; edited length, data length after rejected artifacts

IV. DATA ACQUISITION

In this paper, six ADHD patients are included (Table 1). The diagnosis of disorder is made by the psychiatrist. Subjects 1 and 2 are diagnosed to be ADHD with predominately combined type. Subjects 3 and 4 are diagnosed to be ADHD with predominately inattentive type. Subjects 5 and 6 are diagnosed to be ADHD with predominately hyperactive-impulsive. In this study, eye-opened condition is considered since it is more insightful to evaluate the function of the brain during consciousness. To achieve greater than 90% of the test-retest reliability, the length of data to be analyzed should be longer than 60 seconds. The full explanations of the purposes of this study are given to the patients and their parents before signing the informed consent form.

The BrainMaster Discovery 24E™ (Brain Master Technologies Inc.) is used in this study. 19 channels of EEG are used in this study, i.e. channels Fp1, Fp2, F3, F4, F7, F8, Fz, C3, C4, Cz, T3, T4, T5, T6, P3, P4, Pz, O1, and O2. Linked ears reference (LE) is used. The electrodes are located according to the international 10-20 system. All channels of EEG are acquired with the sampling rate of 256 Hz, 24 bits resolution. NeuroGuide™ software is used for the signal processing of the QEEG. All parameters are calculated with respected to the z-score of the normative database [3]. This published database includes the EEG over 600 healthy peoples from age 2 to 82 years old.

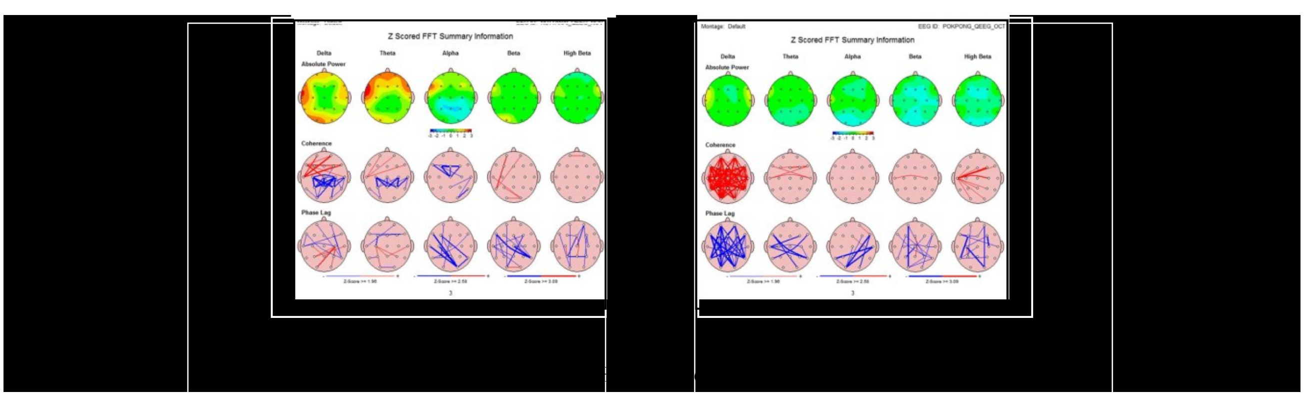
V. RESULT

After the 19 channels of EEG are recorded, brain map for the absolute power (shown in the top row), coherence (shown in the middle row), and phase lag (shown in the bottom row) are demonstrated in Figs. 1 and 2. Each brain map is analyzed in five frequency bands separately. The delta bands are shown in the first column. The theta, alpha, beta, and high beta are shown in the second, third, fourth and fifth column, respectively.

Since all parameters are based on the normative database, brain map for the absolute power represents the deviation from the normative database by color. Any locations have the absolute power close to the norm; it will be shown in green. Turquoise, blue, and intense blue appeared at the locations that have the deviation below the normal range. Yellow, orange, and red represent the location that have the deviation above the normal range.

For the coherence and phase lag, they show the relation between any two sites by linkage. Deviation of any pair that closes to norm will not show any linkages. There are three levels of deviation identified by the thickness of linkage. Thin linkage represents less deviation while thicker linkage shows the higher deviation. Blue link means the deviation is below the normal range. Red link means it is above the normal range.

Brain maps of ADHD combined type are shown in Figs. 1(a) and (b). Blue and intense blue appear at the absolute power QEEG especially in delta, theta, and alpha bands. It is less intense in the beta and high beta bands. Most of them appear at central and frontal area. To consider the coherence, they have some abnormal intrahemispheric coherence and some abnormal interhespheric coherence at delta, theta, alpha, and beta. Both patients show the interhemispheric phase lag that deviate below the normal range.



Brain maps of the ADHD with the inattentive type are shown in Figs. 1(c) and (d). There are excessive delta and theta absolute power in the frontal area. Some excessive high beta was appeared at temporal. Consider at alpha and beta bands, brain maps show deficit amount at occipital lobe of both patient while patient 3 keep deficient at central area. The brain maps of both patients illustrate the hyper-coherence especially in the delta, theta, beta, and high beta bands. Both interhemispheric coherence and intrahemispheric coherence are also appeared. Similar with the combined type, patient with inattentive type have the interhemispheric phase lag deviate below the normal range at every band of EEG.

Brain maps of the patients with hyperactive-impulsive type are shown in Fig. 2. Excessive delta and theta of absolute power appears in patient 5. For patient 6, the absolute power of delta, theta, and alpha bands are close to patient 5. Consider at the coherence brain maps, both patients have some interhemispheric coherence links and some intrahemispheric coherence links; however it is very low when comparing with other types of the ADHD. Hyperactive-impulsive type had some phase lag that below the normal range as well but less than other types. For patient 6, we also observe the coherence and phase lag linkages at delta activity.

VI. Discussion

ADHD children with combined type have deficit in delta theta and alpha activity. Therefore, most of their expression symptoms will regulate by the beta and high beta activity. It makes these groups of patients have hyperactivity and impulsivity. In parts of coherence and phase lag, the linkages appear over the whole brain but not much. The children will have inattention problem because the brain have some abnormalities involved with shared information between sites of the brain.

Some differences in absolute power make the ADHD being predominately inattentive but not excessive hyperactivity and impulsive. They have excessive delta and theta in the frontal area. This may lead to their poor attentions because coherence and phase lag also show a lot of abnormal linkages.

For the hyperactivity and impulsive type, the behavior is dominated by the slow wave, we suggest that the children are hyperactive because they try to offset excessive delta and theta activity. By this mechanism, they always show the hyperactivity, these also lead to the impulsive behavior. Coherence and phase lag linkages appear in their brain map as well, but not as dense as the inattentive type. Hence, we may still observe slightly inattention behavior.

Conclusion

In this work, we have studied the brain map of three subtypes of ADHD children via three method of QEEG, i.e. absolute power, coherence and phase lag. This study shows the abnormality of the ADHD brain map deviated from the normal range.

Predominately inattention type has the brain map feature that clearly discriminate from other types. Combines type and predominately hyperactive-impulsive type were distinguished by the absolute power of QEEG but not clearly differentiate with coherence and phase lag. This information is important to the psychologist, psychiatrist, occupational therapist, and neurofeedback therapist for helping them in the process of treatment planning which can lead to the most efficient treatment.

Acknowledgment

This work is supported by the National Research University Funding (NRU) of Mahidol University. The authors would like to thank Dr. Dusit Liknapichitkul and Yuwaprasart Waithayoopathum Child Psychiatric Hospital, Thailand, for recommendation of ADHD children.

References

[1] Thatcher, R. W. "EEG normative databases and EEG biofeedback". Journal of Neurotherapy, 2(4), 1998, pp. 8–39.

[2] Thatcher, R. W. "EEG database guided neurotherapy". In J. R. Evans and A. Abarbanal (Eds.), Introduction to quantitative EEG and neurofeedback, 1999, pp. 72–93. San Diego, CA: Academic.

[3] Thatcher, R. W. "Z-score EEG biofeedback-Technical foundations". St. Petersburg, FL: Applied Neurosciences, Inc., 2004.

[4] Barry, R. J . "EEG coherence in attention-deficit/hyperactivity disorder: a comparative study of two DSM-IV". Clinical Neurophysiol 113(4),2002, pp. 579-585.

[5] Clarke, A. R. "Coherence in children with attention-Deficit/ Hyperactivity Disorder and excess beta activity in their EEG". clinical neurophysiol 118(7), 2007,pp. 1472-1479.

[6] Dupuy, F. E. "Girls with attention-deficit/hyperactivity disorder: EEG differences between DSM-IV types". Clinical EEG Neuroscience 42(1), 2011, pp. 1-5.

[7] Salinsky, M. C., Oken, B. S. and Morehead, L. "Test–retest reliability in EEG frequency analysis". Electroencephalogram Clinical Neurophysiology, 79 (5), 1991, pp. 382 – 392.

[8] Duffy, F., Hughes, J. R., Miranda, F., Bernad, P. and Cook, P. "Status of quantitative EEG (QEEG) in clinical practice". Clinical Electroencephalography, 25 (4), 1994, pp. 4 – 18.

[9] Hughes, J. R. and John, E. R. "Conventional and quantitative electroencephalography in psychiatry". Neuropsychiatry, 11, 1991, pp. 190 – 208.

[10] Tick, L.J. Estimation of coherence, in Spectral Analysis of Time Series, 1966, pp. 133-152. New York: John Wiley.

[11] Suzuki, H. "Phase relationships of alpha rhythm in man". JPN J. Physiol. 24(6):569-86, 1974.