Initial Study on Implementation of the Low-Frequency Wave Markers for the Purpose of Diagnostic Tests' Performance and Neurofeedback Therapy

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Abstract. The paper focuses on automation of signal processing, which also considers analysis of biomedical data, such as EEG. The results of the study prove that this enables a better understanding of signal changes and makes it possible to address some specific disturbances. It also makes it possible to describe the relevant changes in signals mathematically and helps to create markers of various brain disorders. This paper presents the study at the initial stage and focuses on the mathematical markers of concentration disorders associated with Theta waves. The presented markers presented are based on Welch's periodograms. The obtained results are very promising and further studies aimed at refining them are currently being carried out.

Introduction

This paper presents the initial stage of a study focused on potential electroencephalography signal analysis, automation of various processes of signal analysis, and processing of biomedical data such as EEG. It enables a better understanding of signal changes and allows to name some specific disturbances. It also makes it possible to describe the relevant changes in signals mathematically and create markers of various brain disorders. The presented study is still at the initial stage and focuses on mathematical markers of concentration disorders associated with Theta waves. The markers pre-

sented here are based on Welch's periodograms (Sierra-Alonso et al., 2019; Welch, 1967).

Classification of biomedical data is a problem due to the nature of such signals, therefore this task is very challenging; however, classification of spectral power features of EEG data is currently quite well documented. Proper data-classification plays a crucial role in diagnostics and later in choosing the appropriate therapy (Kawala-Janik et al., 2018; Lazar et al., 2019; Martinez-Murcia et al., 2019).

The method described in this paper is based on periodograms, which are one of the Power Spectral Density (PSD) estimators, first applied by Arthur Schuster as early as in 1898. PSD can be defined as the magnitude squared of the Fourier transform of the measured signal's autocorrelation function. Both the mean and variance enable to characterize the PSD estimator (Bartlett, 1950; Rooney & Buck, 2019; Sierra-Alonso et al., 2019; Welch, 1967).

Various brain disorders such as Attention Deficit Disorder (ADD) or Attention Deficit Hyperactivity Disorder (ADHD) are becoming more common nowadays, affecting about 5% of children and adolescents and about 2.5% of adults (Kostick, 2017; World Health Organization, 2015; Asherson et al. 2018). Due to the character of these disorders it is important to adapt the potential therapy individually to the patient's needs. For this reason, one of the increasingly popular therapy methods is Neurofeedback-based therapy (Budzynski et al., 2009).

Research Methodology

The data was recorded at a frequency range of 1–70 Hz. The sampling frequency was 250 Hz. The amplifier used for the study was a Dig-iTrack BF type digital electroencephalograph. The device registers EEG signal in the time domain. In addition, a program dedicated to this device provides QEEG (Quantitative Electroencephalography) analysis. The measuring equipment consisted of a reference electrode, a cup-shaped electrode, measurement interfaces, and a transducer used for analyses/signal pre-processing. Figure 1 shows the measuring equipment.

The Neurofeedback-based therapy in ADHD treatment is still a controversial method compared to pharmacological or behavioral ones; however, it is becoming more and more popular due to the increasing number of publications describing its positive results (Bluschke et al., 2016; Moreno-Garcia et al., 2015; Moreno-Garcia et al., 2019).

Figure 1. The measuring equipment: 1 – reference electrode, 2 – cup-shaped electrode, 3 – wiring, 4 – measurement interfaces, 5 – transducer for analyses/signal pre-processing

The vast body of literature in the Neurofeedback field suggests that specific bandwidths are associated with particular cognitive functions. Deficits or excesses in these frequencies constitute the basis for the diagnosis of certain disorders. For example, it is possible to notice the occurrence of reduced sensorimotor rhythm in the central strip and excess slow wave activity at the front of the head in children with ADHD. Furthermore, in children with ADD, apart from reduced sensorimotor rhythm, distortions in Beta frequency and adjacent excess Alpha activity was observed in quantitative analyses (Hartmut et al., 2016; Schmid et al., 2018; Schonenberg et al., 2017).

In neuropsychology and neurobiology, sensorimotor rhythm is usually associated with external attention and relaxation. In the case of reduced sensorimotor rhythm, symptoms such as tensions in attention, concentration difficulties, or even low mood may occur (Hartmut et al., 2016; Skirrow et al., 2015; Wilhelm et al., 2014).

Based on the authors' professional experience and in-depth literature study, it can be stated that Theta- and Beta-based protocols are usually used in the front of the head or the central line, depending on the patient's needs (Bluschke et al., 2016; Mehran et al., 2015; Schlerf et al., 2015; Schmid et al., 2018; Schonenberg et al., 2017). As the Theta frequency (4–8 Hz) can be recorded mainly in the front of the head, analysis of its values obtained from the 'Fz', 'C3', and 'C4' channels seems to be the most useful in the diagnosis of ADD and ADHD. Diagnostics based on EEG signal

analysis can be performed as a signal analysis in the time domain or after transfer of the recording to the frequency domain (Clarke et al., 2019; Saad et al., 2018; Schonenberg et al., 2017).

For digital analysis, the EEG signal is usually transferred from the time domain to the frequency domain, as mentioned above. These can be various transformations, including the Fast Fourier Transform (FFT) or periodograms. This allows to extract more information from the signal. The application of the power density spectrum (PSD) may give different results depending on the applied method. Among the various methods popular in the PSD analysis is the Least-Squares Spectral Analysis and the simplified Welch's periodogram. Both methods are similar to the Fourier Transform (FT) and the Fast Fourier Transform (FFT). When analyzing the signal in the low frequency range, it is important to properly select the appropriate filtering method before performing the PSD analysis (Bakhshi et al., 2013; Kubacki et al., 2016).

The authors decided to implement the Welch's periodogram method, which is an improved version of the typical (standard) periodogram (Martinez-Murcia et al., 2019; Mostile et al., 2019; Mulkey et al., 2019). The chosen method is the modified periodogram, which is an improved estimator of the Power Spectral Density (PSD) consisting of the time-series divided into segments. The PSD estimates are then averaged and the result is Welch's PSD estimate (Welch, 1967).

The described method relies on the division of length L into segments K , which overlap in points D , where parameter S is the number of new points in each segment. The number of points common to the two neighboring segments is $M-S$. If $M = S$, then the segment overlap is 0%; however, if $S = 0.5M$, then the segment overlap is 50%.

As the Welch's method can cause losses at the signal limits, to compensate them, the segments are often overlapped in the time domain. Therefore, windowing the signal makes this method a modification of the classic periodogram (Welch, 1967; Zhou et al., 2016).

The Conducted Experiments

The authors decided to use Quantitative EEG (QEEG) (Budzynski et al., 2009) in the study. The electrodes were placed above the motor cortex area in the following locations: 'Fz', 'C3', 'C4', and 'Cz', in accordance with the '10-20' system (Homan et al., 1987). In Figure 2 shows the '10-20' system with marked measurement points (Kawala-Janik et al., 2018).

Figure 2. Measurement points (motor cortex area) (Kawala-Janik et al., 2018)

In order to determine the markers for attention disorders associated with the low frequency waves, five boys aged under 14 ($N = 5$) were tested. All the subjects were diagnosed by a neurologist who detected problems with concentration due to ADD-like disorders. Repetitive changes were observed in recordings obtained from the participants. Based on the changes visible in the QEEG analysis, markers of disorders were determined from Welch's periodograms. In the EEG signal, the Theta frequency is seen as equal amplitude.

Results and Discussion

In the study, 14 subjects were tested together with a small healthy control group (one healthy participant) in order to compare the obtained results and to confirm the data regarding markers. Based on the results, two types of disorders were identified, named I and II.

Figure 3 shows an example of excess Theta waves. The rectangle shows excess low waves (Theta), visible as 5 amplitudes recorded within one second. Figure 4 presents a recording of the signal from channels 'Cz' and 'C3' shown in Figure 3 as a spectrogram. The recording was obtained from a patient with ADD.

Figure 3. Excess Theta waves – sample 1

Figure 4. Example of excess Theta waves – spectrogram, sample 1

The results can be presented in a legible form as a matrix with all the important values. In this case, the output is a matrix consisting of 4 lines and 7 columns. The lines are corresponding to the electrodes used for the measurements: 'Fz', 'Cz', 'C3', 'C4', where the columns are associated with brainwave frequencies: 'Delta', 'Theta', 'Alpha', 'SMR', 'Beta1', 'Beta2', and 'Gamma'. 'X' and 'Y' describe the coordinates of the periodogram. Figure 5 presents a sample matrix obtained from the four ('Fz', 'Cz', 'C3', 'C4') measurement points after the Welch's PSD analysis was applied. The matrix contains the maximum coordinates.

X =

	Delta	Theta	Alpha	SMR	Beta1	Beta2	Gamma
Fz	0.1221	4.2725	10.2539	14.4043	17.9443	27.8320	34.1797
Cz	0.1221	4.3945	10.2539	14.0381	17.9443	26.9775	34.1797
C3	0.1221	4.3945	10.2539	13.6719	18.3105	26.7334	36.2549
C4	2.3193	4.2725	10.2539	14.1602	17.9443	26.9775	34.5459

Y =

	Delta	Theta	Alpha	SMR	Beta1	Beta2	Gamma
Fz	3.7147	3.3540	2.4438	-0.0284	3.1189	2.5477	1.2064
Cz	2.0254	2.8370	3.8038	-0.7568	3.2497	3.0025	0.7625
C3	2.7592	3.5266	4.2134	0.1747	1.5153	2.5887	2.1758
C4	2.7776	2.9616	3.9213	-0.4163	3.2182	2.6258	0.9812

Figure 5. Sample matrix

Figures 6–9 illustrate further sample matrices with the obtained values and PSDs for subjects with attention disorders. It can be noticed that they are strongly connected with the low frequency present in signals.

X =

0.2441	6.9580	9.1553	13.5498	16.8457	24.1699	35.8887
3.9063	7.3242	8.6670	13.5498	16.8457	20.8740	39.5508
0.1221	6.8359	9.1553	12.0850	17.3340	22.2168	39.3066
3.9063	7.8125	8.6670	12.2070	16.3574	20.3857	39.5508

Y =

3.6884	3.9243	3.0032	1.5528	-0.6765	-1.2156	-1.0840
3.0615	4.5907	3.9489	1.2512	-0.7270	-2.9122	-0.8763
3.8105	2.1843	5.0554	2.3835	-0.0468	-2.4474	-0.1952
4.0862	5.3880	6.1623	3.1570	0.6886	-2.0506	-0.3645

Figure 6. Matrix – low frequencies, attention disorders, sample 1

Figure 7. PSD – low frequencies, attention disorders, sample 1

X=						
3.6621	5.6152	9.2773	12.4512	18.5547	29.4189	32.3486
0.2441	5.7373	8.9111	13.1836	18.4326	29.4189	37.4756
1.0986	5.6152	9.3994	13.1836	19.5313	28.1982	38.3301
0.2441	6.2256	9.2773	12.4512	17.9443	29.4189	38.3301
Y=						
-0.0413	3.3910	6.5951	0.4751	1.3278	-0.1790	-0.3426
5.5218	3.2176	8.0526	-0.3771	0.7917	-1.0913	-0.8706
7.1662	3.7992	10.3846	-1.7548	0.1515	-0.3870	-0.9713
4.5198	3.1308	8.8017	0.6637	0.6436	-0.8662	-0.2479

Figure 8. Matrix – low frequencies, attention disorders, sample 2

Figure 9. PSD – low frequencies, attention disorders, sample 2

As mentioned above, it is possible to classify disorders into two types, i.e. type I and type II. Type I is excess Theta frequency; in all the cases the maximum is above 5.5 Hz. Type II is also excess Theta frequency; in all cases the maximum is above 5.5 Hz and the SMR value is below 1 dB.

Figure 10. Spectrograms before (a) and after the Neurofeedback therapy (b) for type II

Figure 10 shows the results before (a) and after therapy (b). An improvement in the overall functioning of the subjects and a reduction of the level of stress can be observed. Moreover, the SMR equaled the normal values. Unfortunately, the Theta values were still too high. Such results suggest a continuation of the training provided for type II disorder.

When analyzing the data for one of the boys, a low SMR, below 1.5 dB, was observed in 3 points. What is more, a higher level of stress could easily be observed. Such results may suggest the possibility of distinguishing a third type of attention disorders. Figure 11 shows a matrix with the recorded results.

Figure 11. Sample matrix suggesting type III disorder

Figure 12 shows the PSD for the intermediate type between the first and the second type. Finally, this type was assigned to type I, with SMR above 1 dB. In the authors’ opinion, the use of diagnostic markers based on Welch’s analysis and co-operative maximum values enables as good diagnostics as the currently used methods. These are, however, a much faster diagnostic method which also allows to recognize the cause of the problem.

Figure 12. Welch’ s PSD

Figure 13 shows two types of ADD/ADHD, providing information obtained by analyzing the data using the marker method described above. The two types of markers enable to present the information in question, i.e. Type I with excess Theta only and Type II with low SMR and excess Theta.

Figure 13. Two types of disorders (type I and II) – markers

All the participants who took part in the study were treated with the Neurofeedback therapy. After a series of 10 trainings, they were subjected to follow-up examinations in order to check the improvement. Next, the training protocols used were compared to the obtained results for the markers method. The results showed a relationship between the training protocols SMR/Theta/Beta in the central line and type II disorders. In the case of type I disorder – the training protocols, SMR/Theta in the non-dominant hemisphere, affected the results for the right and the left hemisphere. In order to confirm the obtained results, the signals were additionally analyzed using spectrograms.

Since the markers are to target a specific type of disorder and to facilitate diagnosis and therapy, the modified periodogram method is sufficient. The conducted research proved a dependence between the type of Neurofeedback therapy and type I and II disorders, which suggests the need for standardization of changes in the applied Neurofeedback training protocols.

Final Remarks

In further studies, it is necessary to examine a greater number of children with various concentration disorders. This will help to develop more algorithms that may classify changes present in signals. It would be useful to analyze the training protocols used in children with disorders associated with low frequency waves. The authors are planning to develop algorithms for the therapy of ADD and ADHD disorders.

The second low frequency, i.e. Delta wave, is usually the largest to observe in locations 'Fz' and 'C3'. Based on literature study, data from those locations is mostly analyzed with regards to testing children with ADD and ADHD. Unfortunately, the Delta wave also increases during movement during the test, so in further analyzes it will be important to choose, e.g., a smoothing filter that will allow to create another marker, one that may be based on slow waves such as Delta and Theta, instead of on Theta or Theta/SMR only (Saad et al., 2018).

Creating new markers based on the Delta frequency as well would require consideration of all traffic-specific changes on the Delta frequency. Another aspect is to work on choosing the appropriate filtering.

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