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Objective Evaluation of Therapeutic Effects of ADHD Medication by Analyzing Movements Using a Smart Chair with Piezoelectric Material

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Abstract: Attention-deficit hyperactivity disorder (ADHD) is the most common neuropsychiatric disorder in schoolchildren. Several methods are available to evaluate ADHD therapeutic effects, including the Swanson, Nolan, and Pelham (SNAP) questionnaire, the Vanderbilt ADHD Diagnostic Rating Scale, and the visual analog scale. However, these scales are subjective. In this study, a piezoelectric material was applied to a medical chair to objectively evaluate the therapeutic effect of ADHD medication before and after treatment. A total of 22 patients (18 boys and 4 girls) with ADHD were enrolled. During the appointment, the patients' movements were recorded by the piezoelectric material before being analyzed. The variance, zero-crossing rate, and high energy rate of movements were used to analyze the signal in this study. The results showed the variance, zero-crossing rate, and high energy rate in patients with ADHD all decreased significantly after 1 month of methylphenidate use. Although the hyperactivity subscales of SNAP obtained from parents and teachers demonstrated significant decreases after 1 month of medication, the reduction rate of the three aforementioned measurements decreased more than hyperactivity subscales. This suggests that the use of a smart chair equipped with a piezoelectric material is an objective and useful method for evaluating the therapeutic effects of ADHD medication.

Keywords: attention-deficit hyperactivity disorder; piezoelectric material; variance; zero-crossing rate; high energy rate; smart chair; Swanson; Nolan; and Pelham questionnaire

1. Introduction

Attention-deficit hyperactivity disorder (ADHD) is one of the most common neuropsychiatric disorders, affecting 8–10% of children worldwide [1]. If it is not treated, ADHD may not only affect the patients' functionality during childhood but also cause social and educational problems later in life. Therefore, the early diagnosis and treatment of ADHD is crucial [2]. ADHD treatment may consist of drug therapy, behavioral therapy, or a combination of the two. Neurochemical evidence for ADHD suggests that drug therapy is more effective than behavioral therapy [3]. Although stimulants are widely used for ADHD drug therapy, approximately 20% of children do not respond to these treatments [4]. Several methods are available for evaluating the therapeutic effects of ADHD medication, including the Swanson, Nolan, and Pelham (SNAP) questionnaire [5], Vanderbilt ADHD Diagnostic Rating Scale [6], and visual analog scales [7]. However, these scales are scored by the parents or teachers of the patients, and this can lead to subjective bias during evaluation. Therefore, an objective method of measuring therapeutic effects is essential for monitoring the treatment effects of ADHD.

The advancement of modern sensor technology has led to the development of tiny wireless sensors that are as small as a coin and that can record data for long periods. Materials with such sensors have been used in the research of many medical conditions, such as osteoarthritis, cerebral palsy, Parkinson's disease, and stroke [8–11]. Increased activity is a common characteristic in patients with ADHD compared with those without ADHD [12,13]. From the viewpoints of neural mechanisms of ADHD, ADHD has been linked to abnormal neuronal activity in the basal ganglia (BG) in general, and the main input nucleus of the BG—the striatum—in particular [14]. In the striatum, the dorsolateral regions are associated with the motor territory, the dorsomedial regions are associated with the executive/associative territory and the ventral regions, including the nucleus accumbens (NAc), are associated with the limbic territory [15,16]. The dorsolateral striatum receives excitatory glutamatergic afferents mainly from 'motor' structures, such as the supplementary motor area and the motor, premotor, and somatosensory cortex [17,18], and project mainly to the dorsal region of the globus pallidus and substantia nigra [19]. Multiple studies of human ADHD patients point to the prominent role of the Cortico-BG loop in their pathophysiology [20]. From animal studies, hyperactivity can be produced by pharmacologically increasing the activity of the NAc core using glutamatergic [21,22], cholinergic [23], and dopaminergic [24] agonists. Studies inducing focal disinhibition in different functional regions within the striatum (by blocking GABAA transmission) have produced a variety of hyper-behavioral symptoms such as hyperactivity and stereotypies in primates and rodents [25,26]. According to the aforementioned evidence, hyperactivity is one of main symptoms of ADHD and needs to be monitored during treatment.

First discovered by the Curie brothers in 1880, piezoelectricity is due to the change in the electric polarization of a material in response to applied mechanical stress or strain [27]. The piezoelectric effect is a phenomenon that converts mechanical energy into electrical energy in a material [28]. Therefore, piezoelectric materials can be used to convert human body energy into electricity for powering wearable electronics. This category of sensing materials is of interest because they can be used to diagnose and monitor respiratory disorders, damaged vocal cords, Parkinson's disease, posture and movement, facial expressions, the degree of change of spinal posture, and skin sclerosis [29]. In patients with sleep apnea, Jerrentrup et al. used a piezoelectric esophageal pressure catheter to monitor the work of breathing on a breath-by-breath basis [30]. Piezoelectric materials can sense dynamic changes in pressure in a closed-loop environment with high sensitivity and a wide measurement range. In another study, Chandel et al. used piezoelectric materials to analyze differences between a heel-strike toe-off stance and a flat-strike stance; the latter is one of the primary symptoms in many pathological gaits, including the Parkinsonian gait [31]. Therefore, piezoelectric materials can be used to detect mechanical changes on a medical chair in the consulting room when ADHD patients visit their physicians. This enables the precise measurement of the activities of patients with ADHD before and after medication administration.

2. Patients and Methods

Patients

The study cohort included 22 children with ADHD, all of whom were examined by a pediatric neurologist or psychiatrist and were asked to sit on the smart chair for data to be recorded. All of them visited our department in the morning. Children with a history of epilepsy, intellectual disability, drug abuse, head injury, or psychotic disorders were excluded. An ADHD diagnosis was made according to the Diagnostic and Statistical Manual of Mental Disorders (DSM)-5 criteria, and ADHD severity was evaluated using the SNAP-IV. The 26 items of the SNAP-IV include the 18 ADHD symptoms (9 related to inattentiveness and 9 related to hyperactivity/impulsiveness) and the 8 oppositional defiant disorder symptoms specified in the DSM-IV. Items are rated on a four-point scale from 0 (*not at all*) to 3 (*very much*). The SNAP-IV is one of the most used instruments for measuring ADHD symptom severity [32,33]. It is composed of all the key symptoms for ADHD and oppositional defiant disorder (ODD) as described in the Diagnostic and Statistical Manual of Mental Disorders, 4th ed. (DSM-IV) [5]. Studies including school- and clinical-based samples from multiple countries have shown good test–retest reliability and high internal consistency for the parent and/or teacher forms of the SNAP-IV [32,34–36]. ADHD is diagnosed based on the patient's symptoms into one of three subtypes: inattentive (ADHD-I; inattentive symptoms and few or no hyperactive symptoms), hyperactive/impulsive (ADHD-H; hyperactive or impulsive symptoms and few or no inattentive symptoms), or combined (ADHD-C; both inattentive and hyperactive symptoms) ADHD. In the present study, we enrolled 22 patients (18 boys and 4 girls). The mean age of patients was 8 years and 4 months ±2 years and 6 months. All 18 boys had ADHD-C; two girls had ADHD-C, and two girls had ADHD-I. Written informed consent was obtained from a family member or legal guardian of each participant. This study was approved by the Institutional Review Board of Kaohsiung Medical University Hospital (KMUIRB-SV(I)- 20190060).

This study used the smart chair, which was connected to a recording device, to assist in the measuring therapeutic effects of ADHD (Figure 1). The piezoelectric material was installed in the chair cushion. A piezoelectric material is a dielectric material that transforms mechanical stress into electrical charge. When mechanical stress is applied to the piezoelectric material, the piezoelectric material simultaneously generates an equal amount of charge on its surface. The positive and negative charges on the surface of the material gradually neutralize, and the potential eventually decays to zero. The material must be repeatedly stretched and compressed for electricity to be continuously generated. A ceramic piezoelectric material was used in this study, and the piezoelectric voltage constant was approximately 300 pC/N. The recorder sampled the signal at a sampling rate of 150 s/s, the voltage range was ±7 mV, and the digital signal was stored at a 12-bit resolution format. The recorder was powered by a battery and could record data continuously for more than 10 h. To ensure precise analysis for each patient, we excluded the signals indicating when the patient initially sat down, finally stood up, or moved while not sitting on the chair. In this study, a piezoelectric material was inserted into a medical chair, and the chair's outward appearance was unchanged. We then used this chair to measure the movements of patients with ADHD to analyze the therapeutic effect of ADHD medication (Figure 1).

Figure 1. Architecture of the detection system.

When the patients visited a doctor, they sat on the medical chair. During the appointment, the patients' movements were recorded before being analyzed. An inherent problem with this system was noise, which interfered with the signal during transmission and resulted in signal distortion. Such noise meant that signals for an empty chair were at a nonzero level. Therefore, this study only recorded the signals from patients' movements, and all other signals were regarded as noise. This was accomplished by using the Kalman filter, which filtered out noise and retained signals that indicated actual movement. The system was also capable of detecting different movements. Figure 2 shows the waveforms of sitting still, standing up, sitting down, swaying back and forth, and swiveling, demonstrating that the system could clearly represent the behavior of the patients on the medical chair.

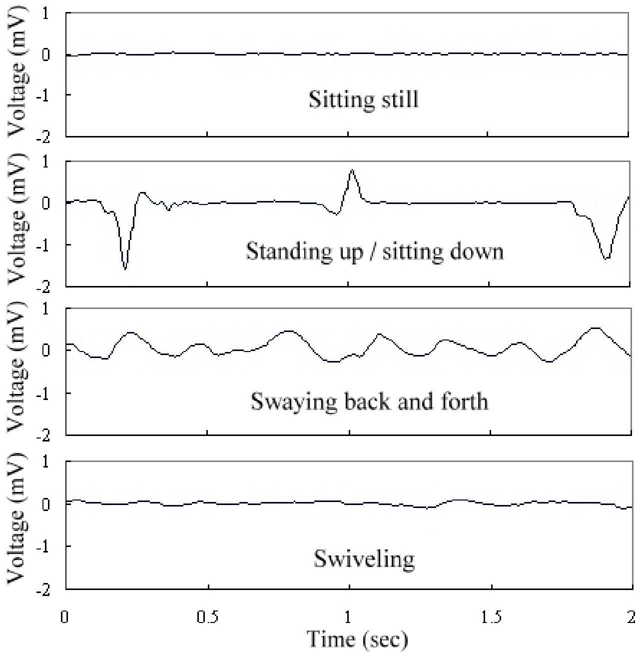

Figure 2. Waveforms of different movements.

Patients with ADHD tend to fidget while sitting down, and this characteristic can be quantified through the variance, zero-crossing rate, and high energy rate. These factors were used to analyze the signal in this study.

A greater variance indicated greater fidgeting by the patient and was defined as follows:

$$VAR = \frac{1}{N}\sum_{n=1}^{N}(x(n) - \overline{x})^2 \quad (1)$$

where $\overline{x}$ represents the mean of a given signal with N samples and $x(n)$ is the nth sample.

The zero-crossing rate refers to the proportion of the signals that cross zero within a period. The zero-crossing rate was defined as follows:

$$ZCR = \frac{1}{2N}\sum_{n=1}^{N-1}|\mathrm{sgn}[x(n)] - \mathrm{sgn}[x(n-1)]| \quad (2)$$

$$\text{where } \mathrm{sgn}[x(n)] = \begin{cases} 1, x(n) \geq 0 \\ -1, x(n) < 0 \end{cases}$$

A higher zero-crossing rate indicates that the participant moves more frequently. The signal is also generated when the participant sits still.

A high energy rate over a threshold Dv was used to identify when a participant made overly large movements. In this paper, Dv was set as a reasonable value of 0.05 mv. This value can distinguish sitting still from other actions.

$$HER = \frac{1}{N}\sum_{n=1}^{N} ture[|x(n)| \geq D_v] \tag{3}$$

$$\text{where } ture[|x(n)| \geq D_v] = \begin{cases} 1, |x(n)| \geq D_v \\ 0, |x(n)| < D_v \end{cases}$$

The high energy rate also indicated the cumulative time in which the patients made overly large movements.

3. Results

In this study, 20 of 22 patients had ADHD-C, and, therefore, most of the recruited patients exhibited hyperactive symptoms. The mean durations of analyses before and after treatment were 329.74 ± 182.33 and 244.18 ± 81.12 s, respectively.

The SNAP scores obtained from parents before and after 1 month of methylphenidate treatment were 42.61 ± 12.05 and 37.72 ± 12.72 (p = 0.1438), respectively; the SNAP scores from teachers before and after 1 month of treatment were 38.76 ± 11.81 and 32.15 ± 15.19 (p = 0.082), respectively (Table 1). SNAP scores, given by the parents and teachers, did not differ between before and after 1 month of medication. However, when we looked at hyperactivity subscales obtained from parents and teachers, both of them demonstrated significant decreases after 1 month of medication (Table 2).

Table 1. Demographic data of patients with ADHD.

Sex (M/F)	Age	Subtype (C/I)	SNAP Score Before Medication	SNAP Score After Medication	Reduction Percentage
18/4	8y4m ± 2y6m	20/2	42.61 ± 12.05 (parents) 38.76 ± 11.81 (teacher)	37.72 ± 12.72 (parents) 32.15 ± 15.19 (teacher)	11.48% 17.05%

Table 2. Comparison of subscales of SNAP in patients of ADHD before and after treatment.

Parameters	Before Treatment	After Treatment	Reduction Rate	*p* Value
Inattentiveness (P)	16.00 ± 5.46	14.28 ± 4.78	10.75%	0.3521
Hyperactivity (P)	15.22 ± 5.27	12.00 ± 5.41	21.16%	0.0147 *
Oppositional (P)	11.39 ± 5.02	10.89 ± 5.81	4.39%	0.7088
Inattentiveness (T)	15.00 ± 4.66	15.46 ± 5.49	−3.07%	0.7921
Hyperactivity (T)	14.08 ± 7.12	9.62 ±7.10	31.68%	0.0330 *
Oppositional (T)	9.69 ± 5.38	7.08 ± 5.58	26.93%	0.076

* $p < 0.05$, P: parents, T: teacher.

The variance, zero-crossing rate, and high energy rate in patients with ADHD all decreased significantly after 1 month of methylphenidate use. The variance values before and after 1 month of methylphenidate treatment were 2239.59 ± 3314.47 and 480.36 ± 871.35 (p = 0.0067), respectively; the zero-crossing rate values before and after 1 month of treatment were 1.0112 ± 0.7547 and 0.4499 ± 0.5588 (p = 0.0005), respectively, and the high energy rate values before and after 1 month of treatment were 0.5062 ± 0.2815 and 0.2883 ± 0.2644 (p = 0.0003), respectively (Table 3). Figure 3 shows the raw data of measurements from one patient before and after 1 month of methylphenidate treatment; the patient fidgeted significantly less while sitting after 1 month of treatment. The Pearson correlation coefficient was used to check the correlation between the reduction rate of objective measurements (variance, zero cross rate and high energy rate) and subjective measurements from SNAP. The results showed that the correlation coefficient between the objective and subjective measurements was not significantly correlated.

Table 3. Comparison of variance, zero-crossing rate, and high energy rate values before and after treatment.

	Before Treatment	After Treatment	Reduction Rate	*p* Value
Variance	2239.6 ± 3314.5	480.36 ± 871.35	78.55%	0.0067 *
Zero crossing rate	1.0112 ± 0.7547	0.4499 ± 0.5588	55.49%	0.0005 *
High energy rate	0.5062 ± 0.2815	0.2883 ± 0.2644	43.05%	0.0003 *

* $p < 0.05$.

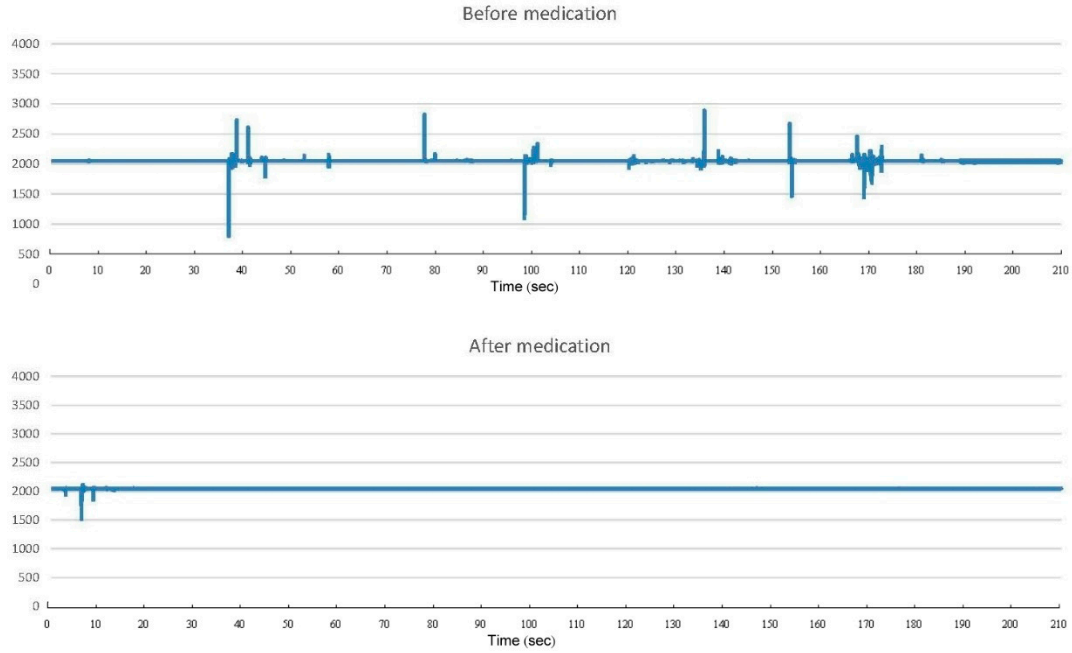

Figure 3. An example of measurements from one patient before and after 1 month of methylphenidate treatment.

4. Discussion

In this study, we found that the variance, zero-crossing rate, and high energy rate significantly decreased in patients with ADHD after treatment with methylphenidate, an ADHD medication. Thus, the variance, zero-crossing rate, and high energy rate may be useful and objective markers for evaluating the therapeutic effects of ADHD medication in patients with ADHD. Although the total scales did not differ between before and after 1 month of medication, the hyperactivity subscales of SNAP obtained from parents and teachers demonstrated significant decreases after 1 month of medication.

The SNAP questionnaire was originally developed to assess ADHD symptoms according to the DSM-III [37,38]. Although several studies have demonstrated that the SNAP score has high validity and reliability [34,39,40], one study reported poor interrater agreement between parents and teachers [5]. In addition, the parents' ratings of inattention and hyperactivity/impulsivity are good predictors for research but not clinical diagnosis. Regarding teacher ratings, only hyperactivity/impulsivity scores are good predictors for both research and clinical diagnosis [40]. The discrepancies between the SNAP scores obtained from the parents and teachers of patients with ADHD can lead to diagnostic uncertainty. In the present study, the hyperactivity subscales of SNAP scores obtained from parents and teachers demonstrated significant decreases after 1 month of medication. For objective evaluation, we used a smart chair equipped with a piezoelectric material to detect the activities of patients with ADHD and noted significant decreases in the variance, zero-crossing rate, and high energy rate values of piezoelectric potentials. The reduction rate of our measurements decreased more than hyperactivity subscales. These results indicate that our method is an objective and convenient tool for evaluating the therapeutic effects of ADHD medications.

Our study is the first to use piezoelectric materials to objectively analyze the therapeutic effects of methylphenidate in patients with ADHD. In addition, the recording instrument was unobtrusive and nondescript, making it easy to use and patients' behavior was not affected by the instrument. The method is a very convenient way to evaluate the therapeutic effects of ADHD medication in consulting rooms.

This study had several limitations. First, although the variance, zero-crossing rate, and high energy rate of piezoelectric materials differed significantly before and after 1 month of methylphenidate in patients with ADHD, the sample size was relatively small. The limited number of patients may cause statistically insignificant correlation between the reduction rate of objective measurements (variance, zero cross rate and high energy rate) and subjective measurements from SNAP. Second, we enrolled children with two of the three different ADHD subtypes, and sample sizes for each subtype, especially ADHD-I, were small; thus, the results may not be generalizable to all ADHD subtypes. Future studies should enroll more patients with different ADHD subtypes to investigate the effects of medication on all three subtypes. Third, children's movements in the consulting room could be affected by some uncontrollable factors, such as food intake on the day of assessment, sleep quality before the assessment, and emotions. A questionnaire will be necessary to investigate the relationship between these confounding factors and children's movements in future studies.

5. Conclusions

Most patients with ADHD have the ADHD-H or ADHD-C subtypes, and hyperactivity is the most prominent syndrome of these two subtypes. In the present study, the variance, zero-crossing rate, and high energy rate values of movements were calculated using piezoelectric materials and used as indicators for the objective evaluation of the treatment effects of ADHD medication. The results demonstrated that the variance, zero-crossing rate, and high energy rate values decreased significantly after 1 month of methylphenidate use. This suggests that the use of a smart chair equipped with a piezoelectric material is an objective and useful method for evaluating the therapeutic effects of ADHD medication, particularly in patients with ADHD-H and ADHD-C.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to ethical considerations.

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