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New Trend of Headaches among High School Students Affected by Smartphone Electromagnetic Pollution Exposures: A Time Series Study

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Abstract Increased prevalence of headaches in teenagers is likely attributable to a number of factors in their daily life, especially the use of smartphones. The smartphone is a device that teenagers spend much time using, which correlates with an increased prevalence of headaches. Here we investigated the relationship between smartphone electromagnetic radiation and headaches in high school students. The time series study was conducted from January-April 2015 among 145 high school students in Chiang Mai Province, Thailand, who were selected by a set criteria. A total of 12,969 headache diary records, smartphone output power, and other variables were collected by a smartphone application and transmitted by email to a researcher every day. Data was analyzed using Generalized Estimating Equation. The majority of the study subjects were female, 17.4 years old on average. The prevalence of repeated headaches was 13.4%. The study revealed smartphone output power in the range of 1.80-1.99x10^{-5}mW affected headache symptoms. (Adjusted odds ratio (OR_{adj}):1.84; 95% Confidence Interval (CI): 1.20-2.81). Meanwhile Lag 5 of daily smartphone output power affected the frequency of headaches (OR_{adj}7.58; 95% CI: 2.02-28.44). The factors of younger age, hands-free device use, and internet use had the strongest association with headaches (OR_{adj}1.33; 95% CI: 1.19-1.49, OR_{adj}3.22; 95% CI: 2.25-4.62 and OR_{adj}2.45;95% CI: 1.94-3.10). The results revealed a new trend of headaches in younger "digital age" people affected by electromagnetic pollutants from smartphones. Limited smartphone use, the use of hands-free devices while talking on smartphones, and an older age to start using smartphones are recommended to prevent smartphone-related headaches in teenagers.

Keywords: *smartphone output power, new trend of headaches, high school students, electromagnetic pollution, time series study*

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1. Introduction

Technological development happens rapidly all over the world. One prominent example of this development is the smartphone, a modern communication device used daily, which generates electromagnetic radiation and has become a source of electromagnetic pollution [1]. Smartphones use electromagnetic wave transmission, transmitting waves at microwave frequencies, sent from the antennas to destination signal numbers. Currently, smartphones are popularly used to meet various needs [2], especially among children and adolescents, or "digital age" people, who have the highest rate of smartphone use with continuously increasing trends [3]. Furthermore, smartphones are sources of electromagnetic energy located incredibly close to users' heads, which can lead to changes in one's nervous system that might cause headaches [4,5].

A headache as a response to electromagnetic emission is often caused by the dysfunction of the endogenous pain control system, which helps adjust pain or response level by sending a signal to the trigemino-cervical complex that regulates the function by a neurotransmitter [6,7]. Thus, electromagnetic radiation from smartphones might be a major contributor to increased headache symptoms. Headache is one of the most prevalently observed neurological issues and is a common problem throughout the world. Recent studies found an increased prevalence of headache in children and adolescents [8,9]. A headache is a type of pain that comes from deep structures in the head referred to as the surface of the head and is caused by changes in the skull involving the excitement of blood vessels and nerves. Headaches may be caused by one or many factors, including pathological, psychological, and environmental factors [10]. Headaches among adolescents affect daily life, education, and quality of life [11,12]. Therefore, control of risk factors is important for headache prevention and maintenance. Although there have been several studies focusing on headaches caused by smartphone use, the effect of electromagnetic radiation on headaches remains unclear.

While it cannot be denied that modern communication devices come with many advantages in our daily life, technology is worthless if not properly used. By the same token, using a smartphone incorrectly can cause physical, mental, and moral injury. Concerned about the health consequences of developing technology, the researchers thus aimed to investigate the correlation between electromagnetic radiation from smartphones and headaches among adolescents as a particularly vulnerable group. This research can provide data leading to guidelines for safe smartphone use and the reduction of headaches based on precautionary protection principles.

2. Materials and Methods

2.1. Study Design and Participants

This prospective time series study was conducted among high school students in Chiang Mai province in Thailand from January-April 2015. The samples comprised 200 students in grades 10-12 who were selected based on a set of criteria. The inclusion criteria required that the subjects have no daily health-related risk behaviors such as liquor, coffee, or tea consumption or smoking, and that they are not undergoing treatment for diseases or health problems diagnosed by doctors. The questions in the headache diary included information about the time when a headache began and stopped, symptoms prior to a headache, symptoms occurring with the headache, headache triggers, headache severity, characteristics of the pain, and telephone conversations conducted over the internet or using hands-free devices or speakerphone. The Pittsburgh Sleep Quality Index (PSQI), anxiety, depression, and smartphone use were also assessed by daily questionnaires. All of the data was recorded every day over a period of 2-4 months (60-120 days) using a smartphone application. The questionnaires were given to 30 students in order to have reliable results by calculating internal consistency with a Cronbach's alpha value of 0.775.

The researchers measured smartphone electromagnetic radiation by measuring smartphone output power (SOP) from the smartphone antenna via an application that requested access to the SOP via the program's framework, saving every five minutes, and transmitting saved data by email to a researcher every day. The researcher measured the error of output power from smartphones using a spectrum analyzer considered to be gold standard. Different brands of smartphone had different power outputs; therefore, an error figure was used to adjust the output power to the same brand of smartphone. The measurement of error in the study was conducted in a normal room, not a chamber room; therefore, the error adjustment might not be accurate. The mean of smartphone output power was collected from the measurements taken at five-minute intervals for 15 minutes. The mean daily dosage data was the sum of the average smartphone output power measured overtime.

2.2. Statistical Analysis

A total of 996 high school students received questionnaire interviews in the first phase of the study, and 200 students were selected from this population by the inclusion and exclusion criteria as subjects of study. To fill in the missing information, the researchers extended the time for information collection from 60 days to 120 days. One hundred and forty-five students submitted complete data, producing in a total of 12,969 records which were coded and analyzed using Statistical Package for Social Science software version 20 to obtain frequency, arithmetic mean, and standard deviation. Relationships between smartphone output power and nocturnal headaches, odds ratio (OR), and their 95% confidence intervals (95% CI) were investigated with a *p*-value <0.05 considered statistically significant. The Generalized Estimating Equation (GEE) was used with data in the same cluster of students to control the confounding effects of such factors as demographic data, anxiety, depression, smartphone use, and sleep quality. In the analysis, therefore, the correlational structure was set and considered the low score of Quasi Likelihood under the Independence Model Criterion (QIC). The Corrected Quasi-likelihood under the Independence Model Criterion (QICC) was used to compare the models under one correlational structure. Low QICC score indicated that the model was a fit.

3. Results

The 12,696 observations were obtained from a total of 145 students. Most of the samples were female, 17.4 years old on average in normal health condition. The prevalence of repeated headaches was 13.4%, with an average headache duration of 3.2±3.7 hours, an average headache frequency of 1.7±1.6 time/day, and an average pain score of 3.2±1.9 (Table 1).

Table 1. The Characteristic of headache presented as percentage unless specified otherwise

Characteristic of headache		N (%)
Headache symptom		
Yes		1705 (13.4)
No		10991 (86.6)
Frequency of headache	Mean± SD 1.7±1.6	Max: 34 Min: 1 (times)
Duration of headache	Mean± SD 3.2±3.7	Max:19.12 Min: 0.04 (hours)
Pain scores	Mean± SD 3.2±1.9	Max: 10 Min: 1

The data on SOP in different brands had been adjusted considering the value of error measured by spectrum analyzers which were considered as the gold standard, to normalize the value for all device brands. The SOP values were then divided into three ranged groups: ≤1.79, 1.8-1.99, and ≥2.0x10^{-5}Mw (Table 2). The SOP in the 1.8-1.99x10^{-5}mW range appeared to be the least prevalent, only 0.6% of the observations, taking place mostly during the evening time.

Table 2. Smartphone output power group by time cycles and daily dose

Time cycle dose and daily dose	Smartphone Output power (x 10^{-5}mW) ≤1.79	1.8-1.99	≥2.0
Daily dose (N/%)	1943 (15.3)	186 (1.5)	10567(83.2)
Morning (N/%)	3597 (31.4)	226 (2.0)	7646 (66.7)
Daytime (N/%)	2479 (20.1)	120 (1.0)	9710 (78.9)
Evening (N/%)	2303 (18.8)	79 (0.6)	9896 (80.6)
Nocturnal (N/%)	2648 (20.9)	301 (2.4)	9747 (76.8)

A statistical test was conducted to evaluate the confounding effects and the relationships between various factors, and no interaction effect was found to exist among them. The odds ratio of headache symptoms, duration of a headache, frequency of headaches, and pain score were adjusted for all other factors using GEE. Auto regression 1 (AR1) was set as the correlational structure due to its lowest QIC. Assessment was made of the characteristics of a headache including headache symptoms, duration, (Table 3 -Table 4), frequency, and pain score (Table 5 - Table 6). The results revealed that younger age, anxiety, and PSQI score were the risk factors of headache symptoms (OR_{adj}1.33; 95% CI: 1.19-1.49, OR_{adj}1.08; 95% CI: 1.04-1.13, and OR_{adj}1.05; 95% CI: 1.02-1.09) (Table 3). The younger age and anxiety were associated with the length of a headache (OR_{adj}1.48; 95% CI: 1.26-1.74, OR_{adj}1.10; 95% CI: 1.05-1.15) (Table 4). Furthermore, younger age, anxiety, and PSQI score were also related to headache frequency (OR_{adj}0.69; 95% CI: 0.62-0.77, OR_{adj}1.11; 95% CI: 1.08-1.14, OR_{adj}1.04; 95% CI: 1.00-1.07) (Table 5). Meanwhile younger age, anxiety, depression, and PSQI score were related to pain score (OR_{adj}0.78; 95% CI: 0.71-0.86, OR_{adj}1.08; 95% CI: 1.05-1.12, OR_{adj}1.04; 95% CI: 1.01-1.07, OR_{adj}1.06; 95% CI: 1.03-1.09) (Table 6). Internet use and not using hands-free capabilities had the strongest association with headache symptoms (OR_{adj}2.45; 95% CI: 1.94-3.10, OR_{adj}3.22; 95% CI: 2.25-4.62), duration of headaches (OR_{adj}2.41; 95% CI: 1.75-3.32, OR_{adj}3.03; 95% CI: 1.74-5.27) frequency of headaches (OR_{adj}1.98; 95% CI: 1.57-2.49, OR_{adj}3.17; 95% CI: 2.23-4.49), and pain score (OR_{adj}2.29; 95% CI: 1.87-2.80, OR_{adj}3.20; 95% CI: 2.21-4.63).

The study showed that smartphone output power in the rage of 1.80-1.99x10^{-5}mW had a greater association with headache symptoms, frequency of headaches, and pain score (OR_{adj}1.84; 95% CI: 1.20-2.81 and OR_{adj}1.55; 95% CI:1.13-2.15 and OR_{adj}1.95; 95% CI: 1.42-2.69) compared to the range of ≥2.00 x 10^{-5}mW. SOP in the range of ≤1.79x10^{-5}mW had an association with the duration of a headache (OR_{adj}1.54; 95% CI: 1.08-2.19). Finally, lag_5 daily SOP had the strongest relationship with frequency of headaches and pain score (OR_{adj}7.58; 95% CI: 2.02-28.44 and OR_{adj}6.89; 95% CI: 1.64-28.98) in the form of a dose-response.

4. Discussion

The present study showed the prevalence of headaches to be 13.4% which is different from headache prevalence rates found in previous studies, which varied across geographic areas, cultures, and sample groups [13]. This study revealed that younger students were more likely to face a relatively greater degree of headache episodes, headache frequency, the pain duration, and pain score. This result contrasted with most previous studies on MP use before the smartphone era which found that headache prevalence varied positively with age [13,14]. This implies that headaches associated with smartphone use is a new trend of headaches among adolescents in the digital era. Previous surveys showed that 31% of children of age 8-10 own and use mobile phones [15].

A study in Korea (2013) found that the average age that children first owned and/or used mobile phones decreased from 12.5 years old in 2008 to 8.4 years old in 2011, suggesting the tendency for children to own and use mobile phones at a younger age [15]. This tendency results in a longer accumulated time of owning and using MP during childhood, supporting the theory that younger students are more likely to get headaches when using a smartphone. Furthermore, the present study revealed that students of an average age of 17.37 years old corresponded to smartphone output power in the range of ≥2.0 x10^{-5}mW compared to those with an average age of 17.88 years old which corresponded to SOP in the range of 1.8-1.99x10^{-5}mW (p<0.01).

Table 3. Odds ratio (OR) of headache symptom and their 95% confidence intervals for each factor and daily dose adjusted for all other factors using GEE (AR1, QIC=8397.22, QICC=8366.53)

Factor	Headache symptom Yes	No	Crude OR	Adjusted OR	95% CI Lower	Upper	p-value
Age, mean ±SD	17.1±0.9	17.4±1.0	0.75	1.33	1.19	1.49	<0.01
Anxiety score, mean ±SD	2.4±2.7	1.7±2.4	1.11	1.08	1.04	1.13	<0.01
PSQI score, mean ±SD	4.0±2.2	3.6±2.0	1.08	1.05	1.02	1.09	<0.01
Total	1705	10990					
Factor	**Total**	**Headache Symptom %**	**Crude OR**	**Adjusted OR**	**95% CI Lower**	**Upper**	**p-value**
Internet use: Yes/ No	1416: 11280	22.2: 12.3	1.98	2.45	1.94	3.10	<0.01
Hand-free use							
No/ Frequent	10477: 951	14.1: 7.8	2.38	3.22	2.25	4.62	<0.01
Sometime/ Frequent	1268: 951	12.0: 7.8	1.76	1.92	1.24	2.97	<0.01
Dose group (x10^{-5}mW)							
1.80-1.99/ ≥2.00	186: 10567	18.3: 13.1	2.01	1.84	1.20	2.81	<0.01

Adjusted by Age, BMI, Vision, Anxiety, Depression, PSQI, Internet use, Hand free use, Device brand, and SOP.

Table 4. Odds ratio (OR) of duration time of headache and their 95% confidence intervals for each factor and daily dose adjusted for all other factors using GEE (AR1, QIC=3473.75, QICC=3458.362)

Factor	Duration pain		Crude OR	Adjusted OR	95% CI		p-value
	>4 hr.	<4 hr.			Lower	Upper	
Age, mean ±SD	17.1±0.9	17.4±1.0	1.45	1.48	1.26	1.74	<0.01
Anxiety score, mean ±SD	2.6±2.8	1.8±2.4	1.10	1.10	1.05	1.15	<0.01
Total	460	12236					
Factor	Total	Duration pain >4 hr. %	Crude OR	Adjusted OR	95% CI Lower	95% CI Upper	p-value
Internet use: Yes/ No	1416: 11280	6.5:3.3	2.06	2.41	1.75	3.32	<0.01
Hand-free use							
No/ Frequent	10477: 951	3.9: 1.7	2.33	3.03	1.74	5.27	<0.01
Dose group ($x10^{-5}$mW)							
≤1.79/ ≥2.00	1943:10567	4.9: 3.4	1.60	1.54	1.08	2.19	0.02

Adjusted by Age, BMI, Vision, Anxiety, Depression, PSQI, Internet use, Hand free use, Device brand, and SOP.

Table 5. Odds ratio (OR) of frequent headache and their 95% confidence intervals for each factor and daily dose adjusted for all other factors using GEE (AR1, QIC=10672.19 QICC=10572.75)

Factor	Total	Correlation frequent pain (*r*)	Crude OR	Adjusted OR	95% CI		p-value
					Lower	Upper	
Age	12691	0.085**	0.702	0.69	0.62	0.77	<0.01
Anxiety score	12691	0.085**	1.12	1.11	1.08	1.14	<0.01
PSQI score	12691	0.042**	1.06	1.04	1.00	1.07	0.03
Lag_5 dose (mW)	12691	0.002	2.81	7.58	2.02	28.44	<0.01
Internet use: Yes/ No	1416/11280	0.4±0.9/ 0.2±0.8	1.76	1.98	1.57	2.49	<0.01
Hand-free use							
No/ Frequent	10477/ 951	0.2±0.8/ 0.1±0.5	2.64	3.17	2.23	4.49	<0.01
Sometime/ Frequent	1268/ 951	0.2±0.9/ 0.1±0.5	2.10	2.14	1.31	3.48	<0.01
Dose group($x10^{-5}$mW)							
1.80-1.99/ ≥2.00	186/ 10567	0.3±0.7/ 0.2±0.8	1.92	1.55	1.13	2.15	<0.01

** p-value=0.01, Adjusted by Age, BMI, Vision, Anxiety, Depression, PSQI, Internet use, Hand free use, Device brand, and SOP.

Table 6. Odds ratio (OR) of pain scores and their 95% confidence intervals for each factor and daily dose adjusted for all other factors using GEE (AR1, QIC=19288.47 QICC=19144.93)

Factor	Total	Correlation score pain (*r*)	Crude OR	Adjusted OR	95% CI		p-value
					Lower	Upper	
Age	12696	0.078**	0.78	0.78	0.71	0.86	<0.01
Anxiety score	12696	0.106**	1.12	1.08	1.05	1.12	<0.01
Depression score	12696	0.083**	1.10	1.04	1.01	1.07	0.03
PSQI score	12696	0.065**	1.08	1.06	1.03	1.09	<0.01
Lag_5 dose (mW)	12696	0.004	1.76	6.89	1.64	28.98	<0.01
Internet use: Yes / No	1416/ 11280	0.77±1.8/0.38±1.2	2.0	2.29	1.87	2.80	<0.01
Hand-free use							
No/ Frequent	10477/ 951	0.44±1.3/0.23±0.9	2.55	3.20	2.21	4.63	<0.01
Sometime/ Frequent	1268/ 951	0.40±1.3/0.23±0.9	2.02	2.11	1.40	3.17	<0.01
Dose group($x10^{-5}$mW)							
1.80-1.99/ ≥2.00	186/ 10567	0.63±1.6/0.41±1.3	2.26	1.95	1.42	2.69	<0.01

** p-value=0.01, Adjusted by Age, BMI, Vision, Anxiety, Depression, PSQI, Internet use, Hand free use, Brand device, and SOP.

The current study also revealed that the factor of age was associated with having headaches in all four periods of the day, and the information recorded supported the observation that young students use smartphones at all time periods.

Higher scores for anxiety and depression both correlated with greater risk of headache episodes, frequency, pain duration, and pain intensity. These results were concordant with previous studies that revealed both anxiety and depression were likely to generate more frequent and more severe headaches and thus were strong risk factors of headaches [16,17].

High PSQI scores appeared to be linked to headache symptoms, frequency, and pain score, which agreed with findings from previous studies that indicated that sleep quality is a contributing factor to frequent headache attacks [18]. Sleep quality is related to headaches, particularly of the migraine type, by triggering the hypothalamus which is linked with the limbic system, the retinohypothalamic tract, and the brainstem aminergic nuclei, as well as with periaqueductal gray (PAG) matter. Provoking the orexin can cause the "rapid-eye-movement sleep off" stage, in which the orexin triggers the ventrolateral part of PAG matter to suppress antinociceptive activity in the trigeminal nucleus caudalis, resulting in a migrainous headache [17]. There is information confirming that sleeping can relieve headaches, while sleep problems can trigger headaches [16], and sleep quality and headache symptoms have a reciprocal relationship.

Internet use is a risk factor contributing to headache episodes, duration, severity, frequency, and all types of headaches (OR_{adj}1.98-2.41; 95% CI: 1.20-3.51). Talking on smartphones via both internet and cellular modes often involves holding the device close to one's head, and the electromagnetic radiation from smartphone to which the users are exposed induces changes in biological reactions, and causes headache symptoms [4]. Electromagnetic radiation while in talking mode is nine times more intense than while in standby mode [19]. A recent study revealed a higher mean of radiated power during a voice over internet protocol, which was assessed at 1.9mW, than the mean of radiated power during voice over circuit switch calls, which was assessed at 0.55mW [20].

The information supported the findings from the present study that not using hands-free devices while talking on a smartphone has the strongest effect on headache episodes, duration, frequency, and pain score (OR_{adj}3.03-3.22; 95% CI: 1.74-5.27). Use of hands-free devices for talking puts some distance between the smartphone set and the user's head, resulting in lower exposure to electromagnetic radiation [21].

The SOP in the present study reflected electromagnetic radiation from smartphone use during a day. It is an important measurement of power emission from the smartphone, which assesses the levels of electromagnetic energy to which the human body is exposed and which is absorbed into tissues [22,23]. SOP varies with the amount of time that one uses the mobile phone. The length of time of repeated or continued smartphone use is thus an important variable for the assessment of exposure to electromagnetic energy [22].

The SOP, which is measured and stored in the device, can be viewed by using an application. SOP values in this study were thus lower than the values of smartphone electromagnetic radiation in other studies which used an external metering device and might be affected upward by radiation from other sources. These values concurred with the average power consumption of a human cell, at $1x10^{-9}$mW [24].

The present findings revealed that headache symptoms, pain score and headache frequency were associated with SOP in the range of $1.80\text{-}1.99x10^{-5}$mW, and headache duration was associated with SOP in the range of $\leq 1.79x10^{-5}$mW. The effects of SOP on headaches were shown to have a nonlinear relationship. There was no statistical evidence that high SOP had higher effects on headaches. However, the study revealed that SOP in the range of $\leq 1.79x10^{-5}$mW and $1.80\text{-}1.99x10^{-5}$mW was linked with headache episodes, frequency of headaches, and severity of headaches, but this relationship was not found for SOP in range of $\geq 2.00x10^{-5}$mW. Our results revealed a nonlinear relationship between SOP and headaches, which concurred with the findings from previous experimental studies on exposure to microwave frequency radiation, which showed that the response only takes place at the specific values but that there was no response beyond the upper and lower values a phenomenon called window effect [25,26]. Similarly, Frey et al. conducted a study by exposing animals to radio frequency radiation at 1200MHz frequency and $2.4mW/cm^2$ and $0.2mW/cm^2$ intensity for 30 minutes. It was found that the dye could penetrate through the blood brain barrier (BBB). Meanwhile, the study of Merritt et al. revealed no difference in BBB permeability at the 1200MHz frequency and $2\text{-}75mW/cm^2$ intensity. The authors concluded that BBB responded to radio frequency radiation only at $2.4mW/cm^2$ and $0.2mW/cm^2$ intensity [6]. Furthermore, numerous studies found that genetic alteration of brain tissue resulted from exposure to microwave frequency radiation and found that this response only took place between 1 and $10\mu W/m^2$ intensity, which was shaped by the window effect, since no response could be found outside this range of intensity [25]. Responses found in different studies had not taken place at a definite time, as they indicated a low level responses depending on the sensitivity of the exposed individual [27]. Therefore, headaches from mobile phone use are characterized by low severity, which is typical for so called mobile phone associated headaches.

Measuring SOP by using the data in the smartphone, rather than outside data, can lead to misclassification of exposure. This observational study is a pioneer study in humans and a panel study measuring the outcomes and exposures for the same sample groups. Controlling individual and environmental confounders was considered in this study. This study relied on the technology by creating a smartphone application which could record data every day, thus avoiding recall bias. Finally, the present study had a large sample size, which enabled an analysis of the effects of slight SOP on the nervous system. Furthermore, the results might be due to the response of the nervous system to the electromagnetic frequency. The authors expect that this study could interest investigators around the world.

5. Conclusion

SOP had a nonlinear correlation with headache symptoms, pain score, and headache frequency. Headaches responded to the delayed effect of the daily dose of SOP in the form of a dose-response. Because repeated exposure is synonymous with continued accumulation, it causes the nervous system to respond to the accumulated effect. Younger age, internet use, and not using hands-free devices while talking on smartphones are risk factors of headache symptoms, producing a new trend of headaches among "digital age" individuals. Finally, higher anxiety, depression, and PSQI scores can contribute to greater headache symptoms. The results showed the influence of electromagnetic pollution, measured by SOP, on a new trend of headaches. Limiting smartphone use, using hands-free devices when talking on smartphones, and older age to start using smartphones are recommended methods for preventing headache disorders.

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