

Analysis of the Mobile Phone Effect on the Heart Rate Variability by Using the Largest Lyapunov Exponent

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Abstract In this study, the effects of electromagnetic fields (EMFs) emitted by GSM900 based mobile phones (MPs) on the heart rate variability (HRV) were examined by using nonlinear analysis methods. The largest Lyapunov exponent (LLE) calculation was used to evaluate the effect of MP under various real exposure conditions. Sixteen healthy young volunteers were exposed to EMFs emitted by GSM900 based MP at two levels from a very low EMF (MP at stand-by) to a higher EMF (MP at pre-ring handshaking and ringing). A blind experimental protocol was designed and utilized with consideration to the physiological and psychological factors that may affect HRV. The results showed that the LLE values increased slightly with higher EMF produced by MP ($P < 0.05$). This change indicates that the degree of chaos in the HRV signals increased at higher EMF compared to low level EMF. Consequently, we have concluded that high level EMF changed the complexity of cardiac system behavior, significantly.

Keywords Heart rate variability · Autonomic nervous system · Mobile phones · Electromagnetic field · Lyapunov exponent · Nonlinear analysis

Introduction

The GSM (Global System for Mobile Communication) Mobile Phones (MPs) are low power radio devices that receive and transmit electromagnetic fields (EMFs). According to the present standards, the maximum powers that MP is permitted to transmit are 2 and 1 W for 900 and 1,800 MHz, respectively [1, 2]. However, since the time division multiple access (TDMA) is used, the average powers transmitted by a MP are never more than one-eighth of these maximum values during the MP conversation. Transmitted power is usually further significantly reduced due to the effects of adaptive power control and discontinuous transmission [3]. It is also well known that, the power of the MP is much higher at the beginning of the communication and changes from 2 W to 100 mW after beginning the communication. While the MP is at stand-by, the output power of MP is at a minimum level. Malaric et al. measured the EMF emitted by MP in various conditions and noticed that these measures are much higher particularly during pre-ring handshaking, ringing and sending SMS (short message service) message than while speaking [4]. They found that the measured peak powers in various stages of the MP operation were 1.5 mW for stand-by and 2 W for ringing and SMS message.

Nowadays, the MPs are frequently used in daily life. Since the MPs are operated, to the users' head close the effects of MPs on the brain and nervous systems have become a popular research area over the last decade. The acute effects of the MPs on the brain, central and autonomic nervous system (ANS) are investigated in many studies [5–10]. Some studies said that HRV analysis can also be used to investigate the effects of MP on the cardiac system and ANS [11, 12]. The analysis of heart rate variability (HRV)

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is a non-invasive clinical technique for indirectly investigating the cardiac and ANS in both healthy and diseased bodies [13, 14]. HRV signals are analyzed by using linear and nonlinear techniques [13].

Some studies have been performed addressing MP effects on ANS activities by using the linear time and frequency domain parameters of HRV recommended by Task Force [11, 12, 15–17]. The results of these studies are controversial. Some of these studies claimed that usage of MP does not affect HRV parameters [11, 15], others say that MP affect some HRV parameters [16, 17].

ANS is not a linear system and nonlinear analysis methods would be more optimal for evaluation of HRV [18, 19]. HRV signals have been analyzed with nonlinear methods in many studies [20–24]. However, only one study investigating the MP effect by using nonlinear measures has been found in literature. In the Ahamed et al.'s study, subjects were exposed to very low level EMF (MP at stand-by). In that study, some nonlinear parameters (scaling exponent and sample entropy) were determined and some differences that are not statistically significant were found [25]. As mentioned above, EMF emitted from MP under pre-ring handshaking and ringing conditions is much higher than under stand-by. High level EMF emitted from MP can affect the nonlinear nature of HRV.

The aim of this study is to investigate the effect of high level EMF emitted from MP on the nonlinear behaviour of HRV. For this purpose, a blind experimental design was performed taking into account some factors that may affect HRV such as physiological and psychological conditions and prandial state of subjects. To determine the effect of high level EMF, during the experiment, MP was run at stand-by (very low EMF) and pre-ring handshaking or ringing conditions (higher EMF) and the results were compared.

Materials and methods

Experimental design

An experimental design, taking into account previous studies performed on MP effect on HRV was used. In some previous studies, a MP attached to subject's ear was run at full power by using special software [12, 15]. In Ahamed et al.'s study, MP is kept at minimum EMF radiation level (stand-by) [25]. In our case, an experimental design that is similar to Andrzejak et al.'s study, was used [17]. MP was run in real usage; meaning the subjects exposure to EMFs transmitted and received between MP and base station, therefore subjects were exposed to real-life exposure. Bernardi et al. showed that speaking changes HRV parameters [26]. Andrzejak et al. pointed out that

results could be affected by actually speaking during the MP call [17]. However; in our experiment, subjects were not speaking during the experiment to prevent this effect.

In Ahamed et al.'s study, MP was kept close to the head and chest [25]. MP is usually kept close to ear in real usage during the call. In this study, the MP attached to the subject's right ear by a bone was called from another MP in different room sequentially at thirty second intervals (MP in pre-ring handshaking, ringing). Therefore, subjects were exposed to a higher EMF than if exposed in stand-by mode. As mentioned above, MPs utilize maximum power during the pre-ring handshaking and ringing stages. During the experiments, a GSM900-based mobile communication service and a commercial MP (Siemens A55) with 0.56 W/kg SAR value were used. Therefore, participants were exposed to EMF with intensity within existing safety limits.

To increase the reliability of our experiment, the following issues were considered. To prevent excitement associated with anticipation and ringer response, MP was set to fully silent mode (vibration and speaker off) because heart rates increase with excitement. A blind protocol was set and subjects were alone during the experiment. Additionally, several studies have indicated that ANS activities change at the postprandial state in respect to preprandial state [27, 28]. Hence, the data were gathered at least 3 h following the subjects' last meal. Furthermore, subjects were requested not to smoke cigarettes, drink caffeine or alcohol beverages nor take any medication on the day of experiment.

Sixteen healthy young volunteers (10 male, six female) participated in the experimental study, with a mean age of 21 ± 2.3 years and a mean weight of 67 ± 13 kg. Each subject was fully informed about the experimental procedure and their written consent was obtained. The experiments were performed at a laboratory on the fourth floor of a building and the distance from the nearest MP base station was about 150 m. Each subject rested for about 5 min in the sitting position and then approximately 21 min electrocardiogram (ECG) records were obtained. The ECG signals were acquired with MP30 (BIOPAC Systems, Inc., Goleta, CA) data acquisition system. Disposable Ag-AgCl electrodes were used. ECG signals were sampled at 1 KHz and transferred to a personal computer (PC) with 10 bits resolution.

In the Andrzejak et al.'s study, there were three sequential periods such as before the telephone call, during the call with use of MP, and after the telephone call [17]. There are three periods in our study as well. Each period in Andrzejak et al.'s study was 20 min. It is a long period for a calling, generally. Considering the average calling duration with MP, each period was set to 7 min in our study. Additionally, our experimental periods were not in

the same sequential order. Eight of the subjects are called during the second period, others are called during the third period. During these call periods, subjects were exposed to higher EMF emitted by MP (pre-ring handshaking and ringing). The call periods are named real exposure periods. These calling periods were selected randomly following blind protocol. The MP was set to stand-by for all subjects outside of real exposure period. These periods are called sham exposure periods.

To understand whether there was an affect originating from the MP, subjects were asked after the experiment whether or not they perceived any sound, vibration and warmth coming from the MP. If they perceived any of these things, we noted it. None of the subjects sensed any vibration or warmth during the experiment. Eight of 16 subjects did not hear any sound. Eight of 16 subjects heard some buzzing but only three of them during MP's ringing period. These observations show that the experimental results were not affected by any sound, vibration or perceived warmth originating from the MP.

HRV signals

The raw HRV signal is obtained from the recorded ECG by finding the time interval between the consecutive heart beats (RR interval). ECG signals can be corrupted by power line interference, electrode contact noise, motion artefact, muscle contraction, modulation with respiration and electronic device generated noise. In this study, QRS detection algorithm of Menrad et al. was used to calculate the time variation of the RR interval [29]. Friesen et al. showed that this algorithm is unsusceptible to the factors mentioned above [30]. For analysis, 360 s duration HRV signals selected from real exposure periods and sham exposure periods. The sham exposure period that is just before the real exposure period was selected as control data.

Nonlinear analysis

According to Kellert, “Chaos theory is the qualitative study of unstable aperiodic behavior in deterministic nonlinear dynamical systems” [31]. The chaotic measures such as poincarè plots, correlation dimension, Lyapunov exponents, Kolmogorov entropy etc. can be used for HRV assessment [13]. For estimation of the chaotic indicators of a system, the attractor of the system has to be reconstructed from the observed variable [32]. An attractor is a set of states in which a dynamical system converges. The nonlinear measures of the system such as Lyapunov exponents, correlation dimensions are calculated based on this attractor [32, 33].

In this study, HRV signal was reconstructed in the m dimensional phase space with delay coordinate τ by using Takens' embedding theorem as [34]:

$$X_i = (x_i, x_{i+\tau}, x_{i+2\tau}, x_{i+3\tau}, \dots, x_{i+(m-1)\tau}) \quad (1)$$

where, X_i is the i th point on the attractor ($i = N-(m-1)\tau$), $x(i)$ is the i th value of the HRV data, m is the dimension of the phase space, τ is the time delay. Time delay (τ) can be selected using some methods such as first zero crossing point of autocorrelation function or first minimum value of average mutual information [32, 35]. In this study, time delay (τ) was selected by using the average mutual information function. There are many existing methods to determine embedding dimension (m) [36–38]. In this case, Cao's method was used as Cao's method does not require large data sets and subjective evaluation, and its computation time is short [38].

The largest Lyapunov exponent (LLE) The Lyapunov exponent is a quantitative measure of the sensitive dependence to the initial conditions and also quantifies predictability of the

Fig. 1 Determination of the time delay (a) and minimum embedding dimension (b) for an HRV signal from real exposure period (subject no: 10)

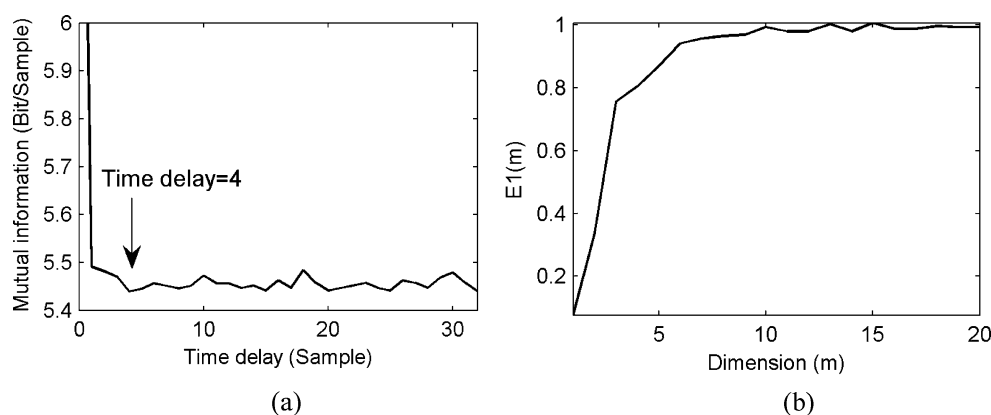


Table 1 The estimated LLE values for sham and real exposure periods

Subject no.	Sham exposure period	Real exposure period
1	0.0069	0.0317
2	0.0267	0.0193
3	0.069	0.0879
4	0.0224	0.097
5	0.038	0.0618
6	0.0386	0.0731
7	0.0142	0.0303
8	0.0276	0.0588
9	0.0348	0.0453
10	0.0113	0.0447
11	0.0469	0.0326
12	0.0613	0.0712
13	0.0523	0.062
14	0.0964	0.0696
15	0.0938	0.1084
16	0.1021	0.1098
mean±SD	0.0464±0.030	0.0627±0.028 ^a

^a $P=0.012$

system. Higher predictability corresponds to lower chaotic degree. The value of Lyapunov exponent increases as the degree of chaos becomes higher. In the system embedded in the m dimensional phase space, the number of Lyapunov exponents is equal to the number of dimension of the phase space hence the system has m Lyapunov exponents. Since a positive Lyapunov exponent indicates chaos [32, 33, 39], the computation of only the largest Lyapunov exponent (LLE) is sufficient for detecting the chaos. Therefore, the LLE measure is most commonly used in nonlinear analysis of physiological signals [20, 21, 23]. Yeragani et al. showed that the HRV variations which can not be sensed by using linear HRV analysis can be determined with LLE measure in some cases [21]. The LLE measure may give an answer to controversial status in linear HRV analysis studied on the effects of EMF from MP on HRV.

For the calculation of the LLE and Lyapunov spectrum from time series signal, several algorithms have been used

[39, 40–43]. In this study, Wolf algorithm is selected [39]. Wolf's method is simple, robust and frequently used for the analysis of experimental data [44].

This algorithm is based on the direct calculation of divergence or convergence of the trajectories on the attractor. There is an Euclidean distance, $\delta x_{(0)}$, at the beginning time (t_0), between the two nearest points, one of them is on the reference trajectory of reconstructed attractor. At a later time t , this initial distance will be evolved to distance $\delta x_{(t)}$. The ratio of these distances gives the evolution of these two points on the attractor in this time interval ($t-t_0$). This procedure is repeated by selecting the new data points at the replacement points on the attractor until the end of data file. The LLE is defined by the average growth rate as [39]:

$$\|\delta x_{(t)}\| = \|\delta x_{(0)}\| e^{\lambda t} \quad (2)$$

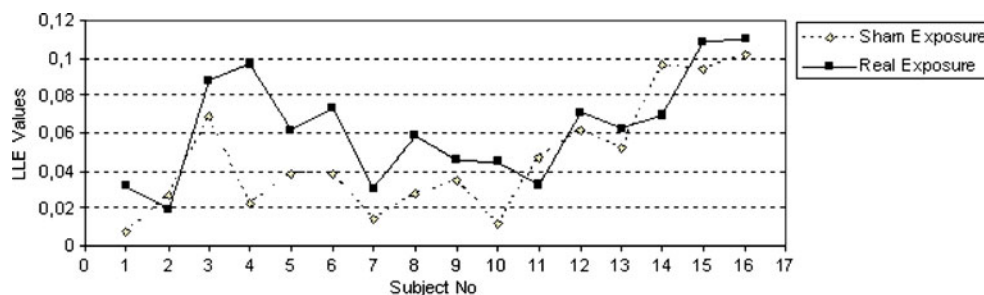
$$\lambda(i) = \lim_{t \rightarrow \infty} \frac{1}{t} \log \frac{\|\delta x_i(t)\|}{\|\delta x_i(0)\|} \quad (3)$$

The Lyapunov exponent values calculated for iterations converges to a constant which is also its average value and this value is known as the true LLE value [39].

The computation of LLE requires an appropriate selection of control parameters apart from time delay and embedding dimension. These parameters are maximum and minimum scale parameters, angular size and trajectory evolution time. The evolution time was selected as 3. The minimum and maximum scale parameters were selected according to the HRV signal amplitude change and angular size was set to 30°. A more detailed explanation of the selection of these parameters can be found in Wolf et al. [39] and Fell and Beckmann [45].

Statistical analysis

Statistical analysis was performed by using the paired student- t test. The Anderson Darling normality tests were applied to the data groups prior to statistical tests and it was seen that they had normal distribution. The student- t test was applied for testing the hypothesis that there is no change in LLE values between the sham exposure (that is

Fig. 2 The variation of LLE values for each subject in real and sham exposure periods

just before the real exposure) and real exposure conditions. The level of significance was selected as $P < 0.05$. If the student- t test P value is lower than this significance level, this hypothesis is rejected and it is accepted that the means of two groups are significantly different from each other.

Results and conclusion

The time delay (τ) and embedding dimension (m) were determined for reconstruction of the HRV signals. The time delay measured as the number of samples was found using the mutual information function [32, 36]. The mutual information function of an HRV signal obtained from real exposure period (subject no: 10) is shown in Fig. 1a. The optimal time delay τ was chosen as 4 for this signal since the mutual information reached the first minimum value. The τ values of HRV signals obtained from real and sham exposure periods were not statistically different (real exposure period: 2.5 ± 1.71 , sham exposure period: 3 ± 1.93 ($P = 0.41$)).

The optimal embedding dimension was found to be 6 according to Cao's method [38] for the same signal and is given in Fig. 1b. The embedding dimensions of real exposure and sham exposure periods were found to be close to 7 (real exposure period: 6.56 ± 1.09 , sham exposure period: 7.00 ± 1.1 , ($P = 0.31$)). Therefore, for the LLE calculation, embedding dimension was set to 7 for all signals. The time delay and minimum embedding dimension analyses were performed by TSTool program [46].

The results obtained from LLE analysis in real exposure and sham exposure periods are given for each subject in Table 1. The variation of LLE values for each subject is also given in Fig. 2. According to Table 1 and Fig. 2, although the LLE values of three of 16 subjects decreased in real exposure period, others increased. The paired student's t test was applied to compare the LLE values of real and sham exposure periods by using Matlab. The LLE of real exposure period was found to be significantly higher than sham exposure period ($P = 0.012$).

According to the results, LLEs of real and sham exposure periods are positive and this indicates that all HRV signals have chaotic behavior. The LLE values increased significantly in real exposure period compared to sham exposure period. This increase shows that there is an increase in complexity of cardiovascular system behavior. Our result suggests that the chaotic dynamics of HRV signals are affected by the relatively high EMF emitted by MP in real exposure.

There is only one study which has investigated the MP effect by using nonlinear measures in literature [25]. In the Ahamed et al.'s study, subjects were exposed to EMF

emitted from MP at stand-by and MP was kept to two different position (close to chest and head). In that study, calculated nonlinear parameters (scaling exponent and sample entropy) were changed according to the MP's position by low level EMF from MP but these changes were not significant [25]. In our study, two different level of EMF from MP were evaluated (MP at stand-by and MP at pre-ring handshaking and ringing conditions) and MP was kept close to the ear. Our results showed that the LLE slightly changes by high level EMF emitted from MP.

A number of studies showed that the usage of the MP affects the cerebral blood flow [7–9], brain electrical activity [10], blood–brain barrier [47] and may also increase the excitability of the brain [5]. If these studies are taken into consideration, there are two mechanisms that may be responsible for the changes in ANS response observed in this study. Firstly, the thermal effect of relatively high EMF can cause a change in blood flow and pressure in the cerebral tissue and ANS may try to compensate this effects. Secondly, the changes of blood–brain barrier and the excitability of the brain by high level EMF may affect the central nervous system. These factors may change the regulation mechanism of the heart rate and LLE.

Our study was limited in that there was not an additional control group. The data obtained from sham exposure periods that are just before the real exposure periods were used as control data. The level of EMF in these periods is very low compared with real exposure periods as mentioned in the Introduction section. We did not measure SAR value which is not accessible for routine evaluation of real-life exposure as mentioned in study of Andrezejak et al. [17].

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