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Heart rate variability in healthy young adults exposed to global system for mobile communication (GSM) 900-MHz radiofrequency signal from mobile phones

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Abstract

Given the large number of mobile phone users and the increasing exposure to radiofrequency electromagnetic field (RF-EMF) worldwide, we aimed to study the effect of RF-EMF related to mobile phones on heart rate variability (HRV). Twenty-six healthy young adults participated in two experimental sessions with a double-blind, randomized and counter-balanced crossover design. During each session, participants were exposed for 26 min to a sham or real 900 MHz RF-EMF, generated by a commercial dual-band Global System for Mobile technology (GSM) mobile phone. We recorded an electrocardiogram at rest during the exposure. We evaluated HRV by time- and frequency-domain analysis. Evaluation of time-domain HRV parameters revealed a statistically significant increase of the standard deviation of interbeat intervals (SDNN) during the real exposure. Other time-domain parameters were not affected. Analysis in the frequency-domain demonstrated that total spectral power and low-frequency band (LF) absolute power were significantly increased during exposure ($p = .046$ and $p = .043$, respectively). However, other parameters were not affected. In conclusion, it seems that most HRV parameters were not affected by GSM signal exposure in our study. The weak effect observed on HRV frequency-domain is likely to represent a random occurrence rather than a real effect.

Keywords

Radiofrequency electromagnetic fields ; Mobile phones ; Autonomic nervous system ; Heart rate variability ; Electrocardiogram

Abbreviations

ANS, autonomic nervous system ; ECG, electrocardiogram ; FFT, fast Fourier Transformation ; GMS, global system for mobile communication ; HF, high frequency band ; HR, heart rate ; HRV, heart rate variability ; LF, low frequency band ; NN, normal-to-normal RR intervals ; pNN50, percentage of successive RR intervals that differ by more than 50 ms ; RR, intervals between successive R peaks ; RF-EMF, radiofrequency electromagnetic field ; RMSSD, root mean square of successive RR interval differences ; SARspecific absorption rate ; SDNN standard deviation of NN

1. Introduction

Mobile phones are a widespread technology, with estimated global active subscriptions close to 7 billion according to the International Telecommunication Union (International Telecommunication Union, 2019). Given this large number of mobile phone users throughout the world, a question that has been raised is whether low-level exposure to radiofrequency electromagnetic field (RF-EMF) from mobile phones affects human health. In this framework, there is still limited knowledge on the effects of RF-EMF related to mobile phones on the autonomic nervous system (ANS), which significantly contributes to the maintenance of the body homeostasis. The regulatory action of the ANS on respiratory, cardiovascular, digestive, endocrine and many other systems is controlled by a number of structures localized in the central nervous system (Jänig, 2008). Indeed, some of the most important integrative centres for ANS functioning are located in the brainstem and central autonomic network, in cerebral and cerebellar regions. Given that they represent a potential source of RF-EMF interference (Fritze et al., 1997; Braune et al., 2002; Huber et al., 2002; Ghosn et al., 2015), RF-EMF emitted by cellular phones may have a potential influence on the ANS.

An example of the close connection between central and autonomic nervous structures is represented by the vagally-mediated control of cardiovascular system and other physiological, affective and cognitive processes (Ramírez et al., 2015; Luque-Casado et al., 2016a, 2016b; Griffiths et al., 2017; Nakano and Kuriyama, 2017; Baik et al., 2019). In particular, cardiac vagal control represents the parasympathetic influence on heart physiology and contributes to heart rate variability (HRV).

Since HRV is controlled by the continuous interplay of both sympathetic and parasympathetic nervous functions (Guidlines, 1996; Berntson et al., 1997; Friedman and Thayer, 1998; Malliani et al., 1998), it is considered to be an index of the ANS modulation. It allows one to assess the interactions between the ANS and the cardiovascular system with non-invasive measurements based on the study of oscillations of the interval between heartbeats.

The effect of RF-EMF related to mobile phones on the ANS has been assessed by measuring HRV. However, the reported findings on the effects of radiofrequency exposure related to mobile phones on heart rate (HR) are contradictory. Some studies on healthy volunteers have reported no effect on the HRV measured during cognitive tests (Wilén et al., 2006) or at rest (Atlasz et al., 2006; Barker et al., 2007; Lindholm et al., 2011; Parazzini et al., 2013; Choi et al., 2014), while others found an effect (Parazzini et al., 2007; Andrzejak et al., 2008; Yılmaz and Yıldız, 2010). Other researchers have investigated the effect of RF-EMF on HRV during sleep of healthy volunteers, showing the absence of statistically significant effects (Mann et al., 1998, 2005) or a modification of HRV parameters due to RF-EMF exposure (Huber et al., 2003). Furthermore, exposure to RF-EMF does not seem to mediate any effect on HRV of subjects who report hypersensitivity to electromagnetic fields (Nam et al., 2009; Kwon et al., 2012; Andrianome et al., 2017).

In general, all these discrepancies in results may be explained by the use of different designs and protocols, exposure intensities, total exposition time or electrocardiogram (ECG) measurement periods. Moreover, it has been suggested that dissimilar results could be related to the subjects' position (i.e. lying or standing) (Parazzini et al., 2007; Misek et al., 2018) or the inspiration/expiration ratio (Béres et al., 2018). Hence, additional studies are needed to provide more information to fill certain gaps in our current knowledge of the effects of the RF-EMF exposure on the ANS.

The aim of the present study was to analyze, in healthy subjects at rest in a relaxed position, the influence of short-term exposure to a global system for mobile communication (GSM) 900 MHz mobile phone during actual use conditions on HRV parameters, evaluated in the time-domain and frequency-domain. First, in order to study the link between HRV and HR, we measured the mean of intervals between successive R peaks (mean RR), which represents the measurement of RR interval lengths in milliseconds. This parameter is directly linked to the HR, where higher values correspond to lower values of HR. We measured the standard deviation of the differences between consecutive normal-to-normal RR intervals (NN intervals) (SDNN), which reflects all the cyclic components responsible for variability, in order to describe the total variability. We assessed the square root of the mean of the squared differences between adjacent NN intervals (RMSSD) to describe the high variability in HR and to estimate the parasympathetic vagal activity on HR. We measured the percentage of adjacent NN intervals that differ from each other by more than 50 ms (pNN50) in order to reflect parasympathetic activity. Moreover, we assessed HRV in frequency-domain, considering the total spectral power, the absolute and relative power in normalized units (nu) of low frequency band (LF), which may be produced by both sympathetic and parasympathetic activity, and blood pressure regulation via baroreceptors primarily mediated by vagal activity, and high frequency band (HF) power, which reflects parasympathetic activity. In order to measure the sympathovagal balance during the RF-EMF exposure, we analyzed the LF/HF ratio.

2. Participants and methods

2.1. Participants

Twenty-six healthy volunteers participated in the experiment (13 females and 13 males, mean age = 23.5 ± 3.1 years). All participants provided informed written consent and were compensated for their participation. All procedures were approved by the local ethics committee (ID N° = RCB: 2011, A01455-36). We selected the volunteers following a routine clinical examination. The mean body mass index of the subjects was 22.3 ± 1.8 (mean ± standard deviation [SD]). Systolic and diastolic blood pressures were 113.3 ± 9.2 and 74 ± 7.7 mmHg (mean ± SD), respectively. Inclusion criteria included regular sleep habits, no medication, no chronic disease or disability, no recent acute illness, no smoking and no neurological or psychiatric illness. We also excluded participants with a history of cardiovascular or neurological diseases. No subject was receiving any medication during the study. All participants were right-handed and had normal or corrected-to-normal vision. Those selected were instructed to abstain from consuming alcohol and coffee or any exciting substances for 24 h before and during each experimental session.

2.2. Experimental design and signal acquisition

Volunteers participated in two ECG recording sessions in a crossover, randomized, double-blind and counterbalanced experimental design (this study was a part of an electroencephalogram protocol (Ghosn et al., 2015)). The two experimental sessions were spaced one week apart and scheduled for each participant at the same time of the day, due to the circadian rhythm of HRV (Coumel et al., 1994). Each recording session comprised three experimental periods: pre-exposure, exposure and post-exposure. We only considered the exposure period in the present paper. During the exposure period, subjects were exposed for 26 min and 15 s to our device with sham or real GSM RF-EMF emission. We conducted the experiment in a dimly lit, electrically shielded room. Subjects were seated in a comfortable chair with a screen placed 1 m in front of them in order to keep their eyes in a well-defined direction. They were asked to relax and breathe regularly during recordings (Eckberg, 1983; Béres et al., 2018).

We recorded HR with a BIOPAC MP150, at a sampling rate of 1000 Hz, by using two electrodes. We placed one electrode at the base of the neck above the right clavicle and the other on the left forearm. We performed ECG within six recording blocks of 3 min each with closed or open eyes to consider possible interaction with cortical activation level (Ghosn et al., 2015). When eyes were open, we asked the subjects to fix their gaze on a spot on the screen represented by a white square in the centre of a black screen.

2.3. Exposure system and dosimetry

Exposure to RF-EMF was performed by a commercial dual-band GSM mobile phone (Nokia 6650) used in our previous studies (Ghosn et al., 2012, 2015). The sham or genuine exposure used a ‘load’ or a ‘dummy load’, respectively. When the telephone was on, the internal circuitry was regularly active, but no radiofrequency power was delivered in space by the antenna. We positioned the mobile phone near the left ear using extendible tubular bandage. Thereby, we could prevent artifacts in the electrocardiographic signal placing the GSM mobile phone at a distance longer than 7.5 cm from any of the ECG electrodes, according to (Buczkowski et al., 2013).

Specific absorption rate (SAR) measurements for the operational frequency at 900 MHz of the mobile phone were conducted using a head phantom. The maximum SARs were averaged on 10 g and 1 g tissue, and the peak value was measured at 0.49 W/kg, 0.70 W/kg and 0.93 W/kg, respectively. The SAR of the sham phone was below the detection level of the system (0.001 W/kg) at any position of the phantom, and we did not detect an electric field on the surface of the sham phone (for more details see (Ghosn et al., 2012; Ghosn et al., 2015)).

2.4. HRV analysis

We used Kubios HRV software (Niskanen et al., 2004; Tarvainen et al., 2014) to automatically detect QRS complexes in ECG signals. We analyzed the data using a peak detection algorithm that identified the R wave of the QRS complexes after removing all motion artifacts. A QRS detection algorithm allowed us to locate a stable, noise-independent fiducial point on the R wave. By comparison with the adjacent morphologic features, the software automatically classified the QRS complexes (and then visually checked) as normal sinus rhythm, atrial or ventricular premature beats or noise. We deduced the NN intervals from adjacent normal sinus beats. We performed standardized time- and frequency-domain HRV analyses on successive 3-min segments of data recorded throughout the exposure recording period, considering the closed eyes and the open eyes recording blocks separately. In this study, we assessed HRV via Kubios HRV software using both time-domain and frequency-domain methods, according to the instructions of the European Society of Cardiology (Guidlines, 1996).

2.4.1. Time-domain analysis

HRV time-domain analysis allows one to quantify the variability in measurements of the time interval between successive heart beats. We calculated the following HRV time-domain parameters: mean RR, SDNN, RMSSD and pNN50.

2.4.2. Frequency-domain analysis

We used a nonparametric fast Fourier transform (FFT) to realize the power spectral density analysis converting time series into the frequency-domain. Our frequency-domain analysis of HRV focused on the low-frequency (LF) band (0.04–0.15 Hz), which reflects sympathetic and parasympathetic tones, and the high-frequency (HF) band (0.15–0.4 Hz), which reflects parasympathetic activity. We assessed the total variability (LF + HF) as the total absolute power in the spectrum for the analyzed region, measured in ms^2. We expressed the LF and HF powers as absolute values in ms2. We also converted the LF and HF powers into normalized units (LF_{nu} and HF_{nu}, respectively) in order to assess the relative power of each band, dividing the period’s power by the total spectral power minus the very low frequency component (i.e. LF + HF). Finally, we expressed the sympathovagal balance with the LF/HF ratio.

2.5. Statistical analysis

For each HRV parameter assessed in the time-domain and frequency-domain, we performed a two-way repeated measures analysis of variance (ANOVA) to determine the effect of the exposure factor (two levels: sham RF-EMF exposure and real RF-EMF exposure), the eyes condition factor (two levels: open eyes and closed eyes) and the interaction between exposure and eyes condition factors. We established statistical significance at $p < .05$. We used StatView software (version 5.0, SAS Institute Inc., Cary, NC, USA) for all statistical analyses.

3. Results

Our HRV analysis in time-domain and frequency-domain are shown in Table 1, Table 2, respectively. All parameters are reported for the open eyes and the closed eyes conditions, during sham and real RF-EMF recording sessions. All the HRV values reported during both experimental sessions are in the normal range (Coumel et al., 1994; Nunan et al., 2010).

Table 1. Heart rate variability values assessed in time-domain.

	Sham RF-EMF Exposure		**Real RF-EMF Exposure**		**Exposure effect**	**Eyes condition effect**
	Open eyes	**Closed eyes**	**Open eyes**	**Closed eyes**		
Mean RR (ms)	846 ± 129	872 ± 143	839 ± 122	868 ± 138	NS	$F_{1,30}$ = 19.9; $p < .001$
SDNN (ms)	53 ± 18	64 ± 25	59 ± 25	71 ± 32	$F_{1,30}$ = 5.6; $p = .024$	$F_{1,30}$ = 23.7; $p < .001$
RMSSD (ms)	41 ± 19	48 ± 25	45 ± 27	53 ± 33	NS	$F_{1,30}$ = 18.3; $p < .001$
pNN50 (%)	23 ± 17	28 ± 20	24 ± 20	29 ± 22	NS	$F_{1,30}$ = 19.1; $p < .001$

Heart rate variability values assessed in time-domain during sham and real radiofrequency electromagnetic field (RF-EMF) exposure with regard to the eyes condition. The corresponding statistical analysis results are shown with respect to exposure and eyes condition factors (two-way repeated measures analysis of variance [ANOVA]). Values are presented as mean ± standard deviation (SD). Statistical significance was set for $p < .05$. RR, intervals between successive R peaks; SDNN, standard deviation of normal-to-normal RR intervals; RMSSD, root mean square of successive RR interval differences; pNN50, percentage of successive RR intervals that differ by more than 50 ms; NS, not statistically significant.

Table 2. Heart rate variability values assessed in frequency-domain.

	Sham RF-EMF Exposure		Real RF-EMF Exposure		Exposure effect	Eyes condition effect
	Open eyes	**Closed eyes**	**Open eyes**	**Closed eyes**		
Total power (ms^2)	2887 ± 2214	3948 ± 3189	3762 ± 4333	5126 ± 5015	$F_{1,30} = 4.3$; $p = .046$	$F_{1,30} = 7.4$; $p < .011$
LF (ms^2)	1264 ± 1213	1561 ± 1589	1689 ± 2562	2526 ± 3425	$F_{1,30} = 4.5$; $p = .043$	NS
HF (ms^2)	706 ± 631	1089 ± 1007	841 ± 933	1244 ± 1466	NS	$F_{1,30} = 14.8$; $p < .001$
LF (nu)	64 ± 19	59 ± 19	64 ± 20	63 ± 20	NS	$F_{1,30} = 7.1$; $p = .013$
HF (nu)	36 ± 19	40 ± 19	35 ± 20	37 ± 20	NS	$F_{1,30} = 6.9$; $p = .013$
LF/HF	3.0 ± 2.7	2.4 ± 2.4	3.2 ± 2.8	2.9 ± 2.6	NS	$F_{1,30} = 6.8$; $p = .014$

Heart rate variability values assessed in frequency-domain during sham and real radiofrequency electromagnetic field (RF-EMF) exposure with regard to eyes condition. The corresponding statistical analysis results are shown with respect to exposure and eyes condition factors (two-way repeated measures analysis of variance [ANOVA]). Values are presented as mean ± standard deviation (SD). Statistical significance was set for $p < .05$. LF (ms^2), absolute power of the low frequency band; HF (ms^2), absolute power of the high frequency band; LF (nu), relative power of the low frequency band; HF (nu), relative power of the high frequency band; LF/HF, ratio of LF-to-HF power; NS, not statistically significant.

Statistical analysis results of time-domain parameters are presented in Table 1. SDNN was significantly higher (+12%) during RF-EMF exposure relative to the sham exposure, during both open and closed eyes conditions. RF-EMF exposure did not significantly alter other time-domain parameters. The eyes condition significantly affected all HRV parameters assessed in the time-domain. All parameters were significantly increased in the closed eyes compared to the open eyes condition. There was no statistically significant interaction between exposure and eyes condition factors.

Considering the statistical results of frequency-domain analysis presented in Table 2, the total spectral power and LF absolute spectral power were significantly higher (+30% and +49%, respectively) during the real exposure to RF-EMF relative to sham with both eyes conditions. The other parameters, HF, LF_{nu}, HF_{nu} and LF/HF ratio, were not affected by the exposure factor. The eyes conditions significantly altered all values of HRV parameters in frequency-domain measurements, except for the absolute LF power. The parameters expressed in absolute value were significantly increased in the closed eyes compared to open eyes condition, while relative LF_{nu} power was decreased with closed eyes. The findings showed that the LF/HF ratio was significantly decreased in closed eyes compared to open eyes condition. There was no statistically significant interaction between exposure and eyes condition factors.

4. Discussion

We performed the present study to determine whether exposure to RF-EMF related to mobile phones (GSM 900 MHz signal) for 26 min could affect the HRV in young healthy adults at rest. We hypothesized that microwave radiations at a frequency of 900 MHz can interact with biological tissue and electrophysiological systems. When a mobile phone is applied next to the ear, we hypothesized that RF-EMF exposure in close proximity to brain structures can alter autonomic nervous centre functioning. Thus, the objective of this study was to analyze whether HRV parameters, which represent a valuable non-invasive approach for assessment of ANS characteristics, are altered during normal mobile phone use. For this purpose, we recorded ECGs in 26 volunteers during the RF-EMF exposure period (real or sham) in a double-blind, randomized and counter-balanced crossover protocol. We analyzed ECGs to assess HRV in both time-domain (mean RR, SDNN, RMSSD and pNN50) and frequency-domain (total power, absolute and relative powers of LF and HF bands and LF/HF ratio) from successive 3-min segments of data recorded with closed or open eyes. All these investigated parameters are correctly evaluated through short-term (i.e. approximately 5 min) and ultra-short-term (i.e. less than 5 min) ECG recordings (Shaffer and Ginsberg, 2017).

When comparing the real and sham RF-EMF exposure, our statistical analysis of the data revealed that most HRV parameters were not different between the conditions. In particular, only SDNN, total spectral power and LF absolute spectral power were significantly higher during the real RF-EMF exposure compared to sham. SDNN represents a connection element between sympathetic and the parasympathetic modulation of HR. However, during short-term resting recordings, the primary source of the SDNN variation is mediated by parasympathetic activity, especially with slow and paced breathing protocols (Shaffer et al., 2014). Previous studies have reported that time-domain HRV parameters, such as SDNN and the standard deviation of the averaged NN intervals (SDANN), are significantly increased during exposure to a mobile phone (Andrzejak et al., 2008). Furthermore, elevated SDNN occurs after RF-EMF exposure with a protocol characterized by symmetrical paced breathing (Béres et al., 2018). The increased SDNN values we noted after RF-EMF exposure might suggest higher parasympathetic activity on HR. However, we did not find other statistically significant modification of time-domain parameters, such as RMSSD and pNN50—both of which are more closely correlated to the vagal action on HR—after exposure.

Likewise, considering the HRV results analyzed in the frequency-domain, we also found that the total power and absolute LF power were significantly increased during the exposure compared to the non-exposure period. There is a weak interaction between LF and RF-EMF exposure with increased values, which is considered to be a consequence of sympathetic response to stand (Parazzini et al., 2007). The total power represents the sum of the energy in all frequency bands, corresponding to the total variability in HRV, while the LF bands reflects sympathetic and parasympathetic tones (Akselrod et al., 1981; Appel et al., 1989). Indeed, during periods with slow respiration rates, vagal modulation can generate cardiac oscillations in HR that cross over into the LF band (Lehrer et al., 2003).

Taken together, this result of SDNN in time-domain, and total and LF absolute powers in frequency-domain, might suggest changes in the autonomic balance, with an increase in vagal activity during the exposure to RF-EMF related to mobile phones. On the other hand, given that HRV is a moderately reliable measurement under controlled and resting conditions from stable ECG (Sandercock et al., 2005), the slight change we observed in our study on the LF or total power, although significant, might not have been caused specifically by EMF exposure. Hence, we considered these results as a chance occurrence rather than a real effect on the ANS. Therefore, our results do not suggest a beneficial effect on ANS mediated by RF-EMF and increased parasympathetic activity. Indeed, despite consensus about the benefits of increased vagal tone, the physiological mechanisms that regulate cardiac autonomic activity are complex and multifactorial, and the level required to provide adequate protection has not yet been determined (Guidlines, 1996).

Nevertheless, our results showed strong evidence that suggests an impact for the eyes condition on HRV parameters. Except for the LF absolute power, all HRV parameters showed a statistically significant difference between the eyes condition (open or closed) during both real and sham RF-EMF recording sessions. We assume that this difference is related to a different state of relaxation between recordings with the two eyes conditions. Indeed, all HRV parameters in time-domain, total spectral power, LF and HF absolute powers and HF relative power were increased during recordings with closed eyes compared to recordings with open eyes. These data suggest a higher vagal tone associated with vegetative functions. Notably, a drowsiness state is characterized by higher parasympathetic rather than sympathetic activity (Vicente et al., 2016). Moreover, lower HRV values with open eyes might be related to a higher impact of sympathetic component on HR, due to the stress aimed to keep the gaze at the fixation point and eventually overcome the drowsiness. Indeed, the LF relative power and LF/HF ratio were higher during the open eyes recordings, compared to the closed eyes ones.

A potential limitation of this study is that we evaluated the effect of GSM mobile phone exposure on HRV in a very specific population of healthy young adults. HRV studies in subjects of different ages or patients with cardiovascular, respiratory or neurological pathologies might present different HRV modulation under mobile phone emission, and thus our results would not be directly generalizable to other populations.

In conclusion, the present study aimed to provide additional information to fill the gap in our current knowledge of the effects of GSM RF-EMF exposure on this topic. Most HRV parameters were not affected by GSM signal in our study. The weak effect observed on frequency-domain HRV LF absolute power or total power likely represented a chance occurrence rather than a real effect.

Credit author statement

Jasmina Wallace: Writing - original draft, Visualization, Writing - review & editing. Soafara Andrianome, Formal analysis, Data curation, Writing - original draft. Rania Ghosn: Investigation, Data curation. Erwan Stephan Blanchard: Formal analysis, Data curation, Writing - original draft. Frederic Telliez: Formal analysis, Data curation, Writing - original draft. Brahim Selmaoui: Conceptualization, Supervision, Writing - original draft, Writing - review & editing, Project administration, Funding acquisition.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

S. Akselrod, D. Gordon, F.A. Ubel, D.C. Shannon, A. Berger, R.J. Cohen
Power spectrum analysis of heart rate fluctuation: a quantitative probe of beat-to-beat cardiovascular control
Science, 213 (1981), pp. 220-222

S. Andrianome, J. Gobert, L. Hugueville, E. Stéphan-Blanchard, F. Telliez, B. Selmaoui
An assessment of the autonomic nervous system in the electrohypersensitive population: a heart rate variability and skin conductance study
J. Appl. Physiol., 123 (2017), pp. 1055-1062

R. Andrzejak, R. Poreba, M. Poreba, A. Derkacz, R. Skalik, P. Gac, B. Beck, A. Steinmetz-Beck, W. Pilecki
The influence of the call with a mobile phone on heart rate variability parameters in healthy volunteers
Ind. Health, 46 (2008), pp. 409-417

M.L. Appel, R.D. Berger, J.P. Saul, J.M. Smith, R.J. Cohen
Beat to beat variability in cardiovascular variables: noise or music?
J. Am. Coll. Cardiol., 14 (1989), pp. 1139-1148

T. Atlasz, L. Kellényi, P. Kovács, N. Babai, G. Thuróczy, L. Hejjel, I. Hernádi
The application of surface plethysmography for heart rate variability analysis after GSM radiofrequency exposure
J. Biochem. Biophys. Methods, 69 (2006), pp. 233-236

S.Y. Baik, C. Kim, S. Kim, D.-W. Yook, H.S. Kim, H. Chang, S.-H. Lee
The moderating effect of heart rate variability on the relationship between alpha asymmetry and depressive symptoms
Heliyon, 5 (2019), Article e01290

A.T. Barker, P.R. Jackson, H. Parry, L.A. Coulton, G.G. Cook, S.M. Wood
The effect of GSM and TETRA mobile handset signals on blood pressure, catechol levels and heart rate variability
Bioelectromagnetics, 28 (2007), pp. 433-438

S. Béres, Á. Németh, Z. Ajtay, I. Kiss, B. Németh, L. Hejjel
Cellular phone irradiation of the head affects heart rate variability depending on Inspiration/Expiration ratio
In Vivo, 32 (2018), pp. 1145-1153

G.G. Berntson, J. Thomas Bigger Jr., D.L. Eckberg, P. Grossman, P.G. Kaufmann, M. Malik, H.N. Nagaraja, S.W. Porges, J.P. Saul, P.H. Stone
Heart rate variability: origins, methods, and interpretive caveats
Psychophysiology, 34 (1997), pp. 623-648

S. Braune, A. Riedel, J. Schulte-Mönting, J. Raczek
Influence of a radiofrequency electromagnetic field on cardiovascular and hormonal parameters of the autonomic nervous system in healthy individuals

Radiat. Res., 158 (2002), pp. 352-356

T. Buczkowski, D. Janusek, H. Zavala-Fernandez, M. Skrok, M. Kania, A. Liebert
Influence of mobile phones on the quality of ECG signal acquired by medical devices
Meas. Sci. Rev., 13 (2013), pp. 231-236

S.B. Choi, M.K. Kwon, J.W. Chung, J.S. Park, K. Chung, D.W. Kim
Effects of short-term radiation emitted by WCDMA mobile phones on teenagers and adults
BMC Publ. Health, 14 (2014), p. 438

P. Coumel, P. Maison-Blanche, D. Catuli
Heart rate and heart rate variability in normal young adults
J. Cardiovasc. Electrophysiol., 5 (1994), pp. 899-911

D.L. Eckberg
Human sinus arrhythmia as an index of vagal cardiac outflow
J. Appl. Physiol. Respir. Environ. Exerc. Physiol., 54 (1983), pp. 961-966

B.H. Friedman, J.F. Thayer
Anxiety and autonomic flexibility: a cardiovascular approach
Biol. Psychol., 47 (1998), pp. 243-263

K. Fritze, C. Sommer, B. Schmitz, G. Mies, K.-A. Hossmann, M. Kiessling, C. Wiessner
Effect of global system for mobile communication (GSM) microwave exposure on blood-brain barrier permeability in rat
Acta Neuropathol., 94 (1997), pp. 465-470

R. Ghosn, G. Thuroczy, N. Loos, V. Brenet-Dufour, S. Liabeuf, R. de Seze, B. Selmaoui
Effects of GSM 900 MHz on middle cerebral artery blood flow assessed by transcranial Doppler sonography
Radiat. Res., 178 (2012), pp. 543-550

R. Ghosn, L. Yahia-Cherif, L. Hugueville, A. Ducorps, J.D. Lemarechal, G. Thuroczy, R. de Seze, B. Selmaoui
Radiofrequency signal affects alpha band in resting electroencephalogram
J. Neurophysiol., 113 (2015), pp. 2753-2759

K.R. Griffiths, D.S. Quintana, D.F. Hermens, C. Spooner, T.W. Tsang, S. Clarke, M.R. Kohn
Sustained attention and heart rate variability in children and adolescents with ADHD
Biol. Psychol., 124 (2017), pp. 11-20

Guidlines
Task force of the European society of Cardiology and the North American society of pacing and electrophysiology - heart rate variability: standards of measurement, physiological interpretation and clinical use
Circulation, 93 (1996), pp. 1043-1065

R. Huber, J. Schuderer, T. Graf, K. Jütz, A.A. Borbely, N. Kuster, P. Achermann

Radio frequency electromagnetic field exposure in humans: estimation of SAR distribution in the brain, effects on sleep and heart rate
Bioelectromagnetics, 24 (2003), pp. 262-276

R. Huber, V. Treyer, A. Borbely, J. Schuderer, J. Gottselig, H.P. Landolt, E. Werth, T. Berthold, N. Kuster, A. Buck
Electromagnetic fields, such as those from mobile phones, alter regional cerebral blood flow and sleep and waking EEG
J. Sleep Res., 11 (2002), pp. 289-295

ITU International Telecommunication Union
Fixed- and Mobile-Telephone Subscriptions, vol. 2019, International Telecommunication Union (2019)
https://www.itu.int/en/ITU-D/Statistics/Pages/stat/default.aspx

W. Jänig
Integrative Action of the Autonomic Nervous System: Neurobiology of Homeostasis
Cambridge University Press, Cambridge, UK (2008)

M.K. Kwon, J.Y. Choi, S.K. Kim, T.K. Yoo, D.W. Kim
Effects of radiation emitted by WCDMA mobile phones on electromagnetic hypersensitive subjects
Environ. Health, 11 (2012), p. 69

P.M. Lehrer, E. Vaschillo, B. Vaschillo, S.-E. Lu, D.L. Eckberg, R. Edelberg, W.J. Shih, Y. Lin, T.A. Kuusela, K.U. Tahvanainen
Heart rate variability biofeedback increases baroreflex gain and peak expiratory flow
Psychosom. Med., 65 (2003), pp. 796-805

H. Lindholm, T. Alanko, H. Rintamäki, S. Kännälä, T. Toivonen, H. Sistonen, M. Tiikkaja, J. Halonen, T. Mäkinen, M. Hietanen
Thermal effects of mobile phone RF fields on children: a provocation study
Prog. Biophys. Mol. Biol., 107 (2011), pp. 399-403

A. Luque-Casado, P. Perakakis, L.F. Ciria, D. Sanabria
Transient autonomic responses during sustained attention in high and low fit young adults
Sci. Rep., 6 (2016), pp. 1-6

A. Luque-Casado, J.C. Perales, D. Cárdenas, D. Sanabria
Heart rate variability and cognitive processing: the autonomic response to task demands
Biol. Psychol., 113 (2016), pp. 83-90

A. Malliani, M. Pagani, N. Montano, G.S. Mela
Sympathovagal balance: a reappraisal
Circulation, 98 (1998), pp. 2640a-2643

K. Mann, B. Connemann, J. Röschke
Cardiac autonomic activity during sleep under the influence of radiofrequency electromagnetic fields
Somnologie-Schlafforschung und Schlafmedizin, 9 (2005), pp. 180-184

K. Mann, J. Röschke, B. Connemann, H. Beta
No effects of pulsed high-frequency electromagnetic fields on heart rate variability during human Sleep1
Neuropsychobiology, 38 (1998), pp. 251-256

J. Misek, I. Belyaev, V. Jakusova, I. Tonhajzerova, J. Barabas, J. Jakus
Heart rate variability affected by radiofrequency electromagnetic field in adolescent students
Bioelectromagnetics, 39 (2018), pp. 277-288

T. Nakano, C. Kuriyama
Transient heart rate acceleration in association with spontaneous eyeblinks
Int. J. Psychophysiol., 121 (2017), pp. 56-62

K.C. Nam, J.H. Lee, H.W. Noh, E.J. Cha, N.H. Kim, D.W. Kim
Hypersensitivity to RF fields emitted from CDMA cellular phones: a provocation study
Bioelectromagnetics, 30 (2009), pp. 641-650

J.P. Niskanen, M.P. Tarvainen, P.O. Ranta-Aho, P.A. Karjalainen
Software for advanced HRV analysis
Comput. Methods Progr. Biomed., 76 (2004), pp. 73-81

D. Nunan, G.R. Sandercock, D.A. Brodie
A quantitative systematic review of normal values for short-term heart rate variability in healthy adults
Pacing Clin. Electrophysiol., 33 (2010), pp. 1407-1417

M. Parazzini, P. Ravazzani, G. Thuroczy, F.B. Molnar, G. Ardesi, A. Sacchettini, L.T. Mainardi
Nonlinear heart rate variability measures under electromagnetic fields produced by GSM cellular phones
Electromagn. Biol. Med., 32 (2013), pp. 173-181

M. Parazzini, P. Ravazzani, G. Tognola, G. Thuróczy, F.B. Molnar, A. Sacchettini, G. Ardesi, L.T. Mainardi
Electromagnetic fields produced by GSM cellular phones and heart rate variability
Bioelectromagnetics, 28 (2007), pp. 122-129

E. Ramírez, A.R. Ortega, G.A.R. Del Paso
Anxiety, attention, and decision making: the moderating role of heart rate variability
Int. J. Psychophysiol., 98 (2015), pp. 490-496

G.R. Sandercock, P.D. Bromley, D.A. Brodie
The reliability of short-term measurements of heart rate variability
Int. J. Cardiol., 103 (2005), pp. 238-247

F. Shaffer, J. Ginsberg
An overview of heart rate variability metrics and norms
Frontiers in public health, 5 (2017), p. 258

F. Shaffer, R. McCraty, C.L. Zerr

A healthy heart is not a metronome: an integrative review of the heart's anatomy and heart rate variability
Front. Psychol., 5 (2014), p. 1040

M.P. Tarvainen, J.P. Niskanen, J.A. Lipponen, P.O. Ranta-Aho, P.A. Karjalainen
Kubios HRV--heart rate variability analysis software
Comput. Methods Progr. Biomed., 113 (2014), pp. 210-220

J. Vicente, P. Laguna, A. Bartra, R. Bailón
Drowsiness detection using heart rate variability
Med. Biol. Eng. Comput., 54 (2016), pp. 927-937

J. Wilén, A. Johansson, N. Kalezic, E. Lyskov, M. Sandström
Psychophysiological tests and provocation of subjects with mobile phone related symptoms
Bioelectromagnetics, 27 (2006), pp. 204-214

D. Yılmaz, M. Yıldız
Analysis of the mobile phone effect on the heart rate variability by using the largest Lyapunov exponent
J. Med. Syst., 34 (2010), pp. 1097-1103