Evaluating the Effect on Heart Rate Variability of Adults Exposed to Radio-Frequency Electromagnetic Fields in Modern Office Environment

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***Abstract*—The objective of the study was to investigate whether heart rate variability (HRV) is an appropriate method to describe potential effects of RF-EMF on humans considering a modern office environment radiation level with the frequencies 1.8 GHz (DECT) and 2.45 GHz (Wi-Fi) and an exposure time of 10 min. The emitters were 1 m distant from the test subjects. The HRV parameters SDNN, RMSSD, LF and HF were recorded from 60 adults in three runs, totaling up to 154 recordings. Effects were evident for the parameter SDNN. In two runs, HRV changed from control to exposure phase, in one run from exposure phase to control. The cofactors smoking, coffee consumption, and the use of strong medications did not modulate EMF effects. HRV seems to be suitable to detect effects of radio-frequency electromagnetic fields on humans under certain conditions. In the future, prolonged exposure and new frequencies (5G) should be included in order to provide a better description of RF-EMF effects in modern office environments.**

Keywords*—*Radio frequency electromagnetic fields; heart rate variability; office environment; Wi-Fi; DECT

I. Introduction

There are a growing number of scientific studies on the effects of RF-EMF on human health [1]. Belpoggi [1] evaluated thousands of studies for the European Parliament in its scoping review. The main discussed harms are cancer promotion [2], decreased fertility [3] and blood-brain barrier disruption [4].

Oxidative cell stress is assumed to be the mechanism of action. In the review by study [5], 100 studies were evaluated. Of these, 93 studies demonstrated microwave radiation-induced oxidative cell damage. All studies were conducted with field strengths below the ICNIRP established limits. For example, [5] describes that oxidative damage occurs at a power flux density as low as 1 mW/m^2, which is 0.002% of the ICNIRP limit [6] (ICNIRP 2020 Guidelines, 50 W/m^2 the limit).

In 2011, the WHO classified RF-EMF as possibly carcinogenic to humans [7]. Meanwhile, a higher classification is demanded by numerous scientists [8, 9].

Most studies are conducted on animals or on cells, few investigate health effects on humans directly [10].

The determination of heart rate variability (HRV) is a well-established method to evaluate the activity of bioregulation [11]. Heart rate variability (HRV) is the variation in the time intervals between two heartbeats and reflects the functional state of the autonomic nervous system [12]. It is a non-invasive marker for autonomic input to the heart [13]. Stress (e.g., mental, workplace-related) usually leads to a reduction of parasympathetic activity and thus to a reduction of the HRV [14, 15].

In a recent review [16] of RF-EMF effects on humans, there are few studies on the effect of RF-EMF on cardiac functions in humans. Parizek et al. [17] state that currently there are few studies that have examined the effect of electromagnetic radiation on HRV in healthy individuals.

The study in [18] investigated the effects of mobile radio (GSM 900 MHz) on heart rate and blood pressure in 10 volunteers. HRV was not recorded. Blood pressure increased after 60 sec. of exposure.

In their provocation study, [19] investigated the effect of mobile radio (900 MHz) on healthy subjects. HRV data differed significantly between treatment and control. The higher LF activity and the lower HF activity might be interpreted towards a shift to sympathetic activity.

This turn is often regarded as a sign of an increased stress level [19]. In the study by [20], 26 young healthy volunteers were used to investigate whether exposure to 900 MHz from mobile phones alters the regulation of the cardiovascular system. There were significant changes in some time domain (including SDNN) and frequency analyses (LF power).

Andrzejak et al. [21] investigated the influence of mobile phone conversation on HRV parameters in healthy subjects. Significant changes were found in the parameters SDNN and SDANN, however, the influence of talking on the results cannot be excluded.

Yılmaz and M. Yıldız [22] found an influence of mobile radio (900 MHz) on the HRV of 16 young healthy volunteers using the Lyapunov exponent calculation. The degree of chaos in HRV increased with the use of mobile phones. Havas et al.

[23] investigated the effect of cordless phone at 2.4 GHz radiation on 25 subjects. 40% of the subjects show changes in their HRV due to pulsed (100 HZ) microwave radiation. A study conducted on 164 police officers by [24] resulted in a change in HRV values. Exposure to the TETRA frequency band (380-395 MHz) occurred directly on the police officers' chest.

In the study of [25], subjects were exposed to a 50 Hz sinusoidal magnetic field. The total power of HRV was significantly lower under exposure than in the control.

The study by [26] showed some effects of 1.8 GHz on time domain HRV of 20 healthy volunteers but depending on breathing rhythm.

The question arises whether HRV is suitable to measure potential exposure to RF-EMF in a modern office environment. In the earlier studies on EMF and HRV, Wi-Fi frequencies were rarely considered, many studies referred to the frequency 900 MHZ, which is hardly used today. In our study, the RF-EMF exposure in a modern office environment should be simulated. For this purpose, exposure to the frequencies (1.8 and 2.45 GHz) took place. After a rest period of 10 minutes, the exposure was performed for 10 minutes. This was followed by another rest period of 10 minutes. The following main hypotheses were formulated:

1) EMF exposure (phase 2) decreases the HRV of the subjects compared to phase 1 (no exposure).

2) After exposure (phase 2), the HRV of the subjects increases again.

The secondary hypothesis was formulated as follows.

3) The cofactors smoking, coffee consumption and the intake of medication change the response of the subjects to EMF.

II. Material and Methods

A. Study Design

The project was a single-blinded provocation study. It was conducted in a laboratory. 60 adult persons were tested in three runs (60, 54 and 40) with a total of 154 observations.

B. Participants

Participants were recruited via advertisements on the campus of the University of Oradea and through direct contact (phone calls, messages and e-mails) from the Research Department, at the University of Oradea and surrounding general contacts in Bihor county.

During the survey period (March 2021 to December 2021), 61 people made contact as a result of the recruitment strategies. Of these, 61 people expressed interest in the study and all 61 came to the first testing session (run 1) and signed the informed consent form and the printed screening form in which general questions (concerning sex, date of birth, profession, use of electronic devices in general and previously during the day of the test, amount of caffeinated beverages consumption, medication usage and cigarettes smoking previously during the day of the test, contact details - address, phone number, e-mail address) were answered. The only inclusion/exclusion criteria were related to age: the subject must be over 18 years old (adult). At the beginning of the testing session, other parameters were asked to be introduced in the ECG-Holter database (as height, weight and acute or chronic somatic or psychiatric diseases). Additionally, the participants in the test signed an internal form of SARS-COV-2 declaration in order to prevent the spreading of the disease. Prior to the start of every testing session, participants were asked to refrain from smoking or consumption of caffeinated beverages in the preceding two hours of the experiment. Additionally, participants were asked to wear casual clothing. Participants were asked about consumption of caffeinated beverages, smoking, and medication use (for heart and circulatory problems, diabetes, endocrine issues and lupus).

Of the 61 participants in the first run, 1 was excluded from the data processing of the results and statistics, because of an existing pacemaker that made the study irrelevant for the person in cause. Hence, for the first run, the results and statistics considered data from the remaining 60 participants. In the second run, from the initial 61 people, 54 participated in the test. In the third run, 40 people from the 54 participating in the second run took part in this third testing session.

In all three runs the participants in the experiment completed the consent form, the questionnaire and the CORONA-form. Demographical data for all three runs are presented in Table I. In all three runs of the experiment, the testing sessions were developed during daylight, between 13:00 and 16:00.

TABLE I. Sociodemographic Data of the Participants

Period of execution	Age			Sex	
	18-29 years	30-49 years	50-65 years	Male	Female
Run 1 (4/3/2021-4/5/2021)	20	22	19	31	30
Run 2 (17/5/2021-23/6/2021)	18	20	16	28	26
Run 3 (4/10/2021-7/12/2021)	13	14	13	20	20

C. Experimental Design and Procedure

In a room with low background exposure, subjects were exposed to DECT (1.8 GHz) and Wi-Fi (2.45 GHz) in a relaxed sitting position, with a 5-lead ECG Holter monitoring the cardiac functions. The distance to the transmitters was approx. 1 m. The measurements took place over 30 minutes.

In the first 10 minutes (OFF1) the transmitters were switched off, in the second 10 minutes the devices were switched on (ON) and in the third 10 minutes (OFF2) the devices were switched off again. In addition, there were considered also 10 minutes for completing the forms, before the test (the personal questionnaire, participation consent and Corona declaration), with no exposure at DECT or Wi-Fi.

The entire procedure and the subject’s medical data were managed and supervised by a medical doctor. The subject was alone in the room during the test, having just basic information about the aim of the test (e.g. some health parameters will be measured under controlled Wi-Fi emission levels: minimum almost zero and normal for an office environment). The subject was not aware when the signals were ON or OFF, being completely blinded in relation to the phases of the experiment. The flux density on the subject was approx. 16000 μW/m² on the ON phase of the experiment and almost negligible during the rest. A technical staff member was present during the entire experiment in room 2 to ensure the experiment ran correctly and was identical during each test.

The measurements were carried out in early spring 2021 with 60 subjects (run 1), in summer 2021 with 54 subjects (run 2) and in late autumn 2021 with 40 subjects (run 3).

Participants were recruited via advertisements on the campus of the University of Oradea and through direct contact (phone calls, messages and e-mails) from the Research Department, in the University of Oradea and surrounding general contacts in Bihor county.

D. Technical Set-up of the Intervention

1) General technical prerequsite for the experiment: The location for the experiment was chosen in a remote seminar room of the University of Oradea, where no other wireless networks or other wireless devices were present. For the active phase of the experiment common commercially available wireless equipment was used, as the ones often encountered in ordinary working environment as classrooms or offices (SOHO – Small Office, Home Office - wireless router or DECT cordless telephone equipment). No modifications of any kind have been made to the equipment, which complies with current standards.

Before the experiments, measurements of the radiation levels in the room were done using a radio spectrum analyzer (Spectran HF-4040) [27]. The power level of background radiation in the frequency band of Wi-Fi networks was about -80 dBm. This relatively low level is due to the remote location and the construction specific features of the room, making the location well suited for the experiments.

To generate the signals transmitted over the Wi-Fi network, it was sufficient to use a single wireless access point (router) and a single laptop connected to it. It is not necessary to use more PC/laptop equipment as only one device will transmit at a time, due to the IEEE 802.11 specification. Due to this modus operandi, at a certain time the signals will always come only from one station even if more than one device is connected to the network. Hence, only one entity will transmit at a time, so the peak RF radiation level does not increase if more devices are connected to the network.

To maximize the radio frequency signal level, forced traffic was generated in the network. Traffic generation is done by transmitting data over the network at the maximum speed the network can provide, using specialized software. The speed at which data will be transmitted is influenced by several factors: the distance between the laptop's wireless adapter and the router (and therefore the signal level) or disturbances due to other nearby Wi-Fi networks, especially if they are located on radio channels close to the network under test.

Also, interference caused by other devices in the 2.4 GHz band (microwave ovens, Bluetooth devices, etc.) can affect the network's operation.

The location for the experiments was specifically chosen to minimize the influence of these external disturbing factors.

There were no other Wi-Fi networks in the area and no other equipment producing radiofrequency radiation in the 2.4 GHz band was present in the test location. The network was thus able to transmit radiofrequency packages with almost optimal efficiency.

To achieve a high level of traffic, a large file can be downloaded over the network, or specialized software packages able to determine the maximum transfer speed in a network can be used. For the traffic generation in the experiment, the iperf software package was used [28]. Iperf is a program for bandwidth measurements between two or more computers or devices on a local area network or the Internet network. Iperf usage guarantees high and constant network traffic.

To ensure blinding and to avoid any influence of an experimenter on the results of the experiment, the control of the applications was done using remote desktop software. The software used to remotely control the experiment was VNC (Virtual Network Computing) which is a graphical desktop-sharing application to remotely control another computer, allowing the transmission of keyboard and mouse input from one computer to another, while sharing graphical-screen updates, over a network [29]. VNC was used to remotely turn on and off the wireless adapter on the laptop.

The connection diagram is shown in Fig 1. To keep the connection with the laptop and to be able to control it even when the wireless connection is switched off, the laptop is also connected to the router via a wired connection. The control through VNC is done over this wired connection. The computer controlling the experiment remotely, located in an adjacent room, was also connected to the network. The wireless interfaces of the router and the laptop were remotely controlled, to simultaneously switch on and off the wireless signal throughout the phases of the experiment.

During the experiments, the human subjects were exposed to Wi-Fi signals emitted by the router and laptop, superimposed with signals corresponding to a DECT phone call. In this regard, a DECT base station was placed in the room where the subject was located, to which a cordless telephone receiver was connected via radio waves. The DECT signals were turned on and off at the same time as the Wi-Fi signals were, by connecting and disconnecting the DECT base station from the power source and by turning the DECT phone on and off.

E. Analysis of the Signals used in the Experiment and Assessment of the Exposure Levels

The level of Wi-Fi radiation and DECT was measured using multiple devices. First, the emitted power was assessed using a radio spectrum analyzer (Aaronia HF-4040). These measurements were performed over the entire duration of the experiment (30 minutes) and the level of radio power received by the device was recorded. These measurements allow an overview of the wireless devices' power variation over time.

During the ON phase the power received by the spectrum analyzer does not show large variations, around -28dBm. This is considerably higher than the background radiation that was present in the OFF phases, when the power level is also constant, with a value below -80dBm.

The recording of the radiation power level was analyzed using a Matlab program to obtain a visualization of the radio-frequency levels. This 3D visualization basically combines the previous two figures into power analysis in both time and frequency domains and is presented in Fig. 2.

Wi-Fi signals in the 2.4 GHz frequency band were used in the experiments.

In Fig. 2 it can be seen that Wi-Fi channel 7 (2431-2453 MHz) in the central region of the frequency band intended for those networks was chosen, to make the experiment results as relevant possible for the whole Wi-Fi frequency band.

Most Wi-Fi networks nowadays use this frequency band, and networks in the 5 GHz band are generally scarcer.

A Panasonic KX-TG1611FX DECT station was also placed near the subject and activated at the same interval of time as the router. The DECT devices (the phone and the base station) were also turned on and off synchronized with the Wi-Fi devices.

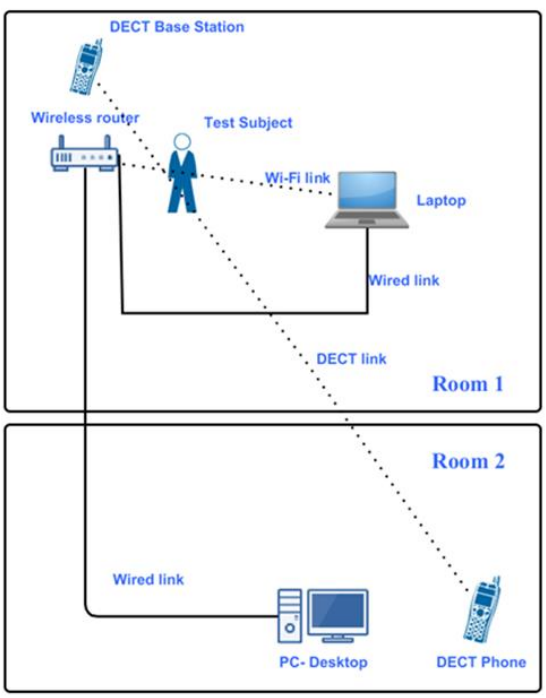

Fig. 1. The connection diagram.

The most relevant measure of the exposure levels is made in the literature using as reference the maximum power density values, which show the amount of power falling on an area. These are usually expressed in milliwatts per square meter (mW/m²). From this perspective the exposure levels were measured using a specialized broadband device (HF59B RF-Analyzer from Gigahertz Solutions), which allows rapid measurement of this parameter. The results for the power flux density are presented in Table II.

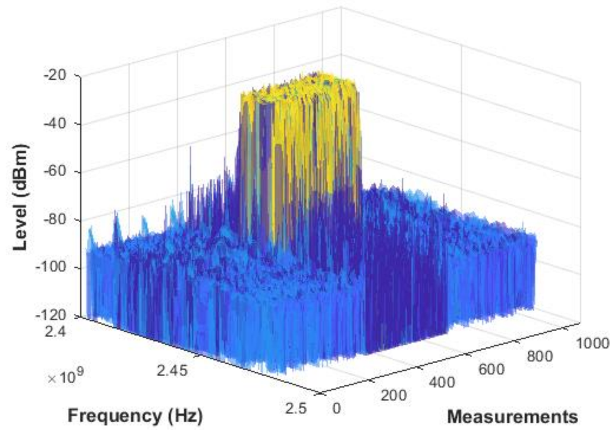

Fig. 2. 3D view of the Wi-Fi signal power levels during the phases of one of the experiments.

TABLE II. POWER FLUX DENSITY MEASURED DURING THE PHASES OF THE EXPERIMENT

	Power flux density values in μW/m2	**Method**	**Percentage from ICNIRP limits[b]**	**Duty factor for Wi-Fi and DECT transmission**
OFF phase, no Wi-Fi, no DECT	150	Peak hold	-	-
	5	RMS	0.0000125 %	
ON phase, with Wi-Fi, no DECT[c]	10 000	Peak hold	-	100 %
	50	RMS	0.000125 %	
ON phase, Wi-Fi and DECT	16 000	Peak hold	-	100 % Wi-Fi + 7.1% DECT[d]
	110	RMS	0.000275 %	

[a.] The measurements were made at approx. 1 m from the Wi-Fi router and the DECT station used to generate electromagnetic field during the experiment, the same distance the participants on the experiment were positioned during the test.

[b.] The limit was considered as 40W/m2 (Reference levels for general public local exposure, aver-aged over 6 min, to electromagnetic fields from 100 kHz to 300 GHz - unperturbed RMS values [6])

[c.] This situation was not exactly met during the experiments, it is considered just for comparative analyze reasons, to emphasize both Wi-Fi and DECT emissions.

[d.] See ETSI TR 103089 Standard for DECT transmissions [40]

F. Measurements and HRV Measures

In order to acquire data on HRV (heart rate variability) an ECG device was used along with its software. The electrocardiogram recorder was a BTL-08 manufactured by BTL with BTL CardioPoint software H600 version. The BTL-08 Holter [30] is an advanced ECG electrocardiogram recorder. It records the electric activity of the human heart using electrodes attached to the patient's chest for short or long periods of time (maximum 48 hours).

The BTL-08 Holter device is intended for use in an electromagnetic environment in which radiated HF disturbance is controlled. In order to meet the requirements for the ECG Holter proper functioning in Wi-Fi radiation presence, the distance between the electromagnetic radiation source (the Wi-Fi devices) and the Holter device should be greater than 0,22 meters according to the ECG devices manufacturer's specifications. This condition was met during the whole experiment.

Frequency and time domain analysis are sophisticated methods of determining how much of a signal is contained within one or more frequency bands (ranges).

In the case of HRV, research has revealed that particular frequency bands are associated with physiological phenomena such as parasympathetic nervous system activation. HRV measures in the Frequency Domain include:

High-Frequency power (HF): frequency activity in the 0.15 - 0.40Hz range

Low-Frequency power (LF): frequency activity in the 0.04 - 0.15Hz range

Obtaining accurate low frequency measurements requires reading times of mini-mum four minutes or more. Measured frequency values are also expressed in Hertz (Hz) or milliseconds (ms) or milliseconds squared (ms2). The HRV parameters SDNN, RMSSD, LF and HF were recorded (see Table III).

TABLE III. RECORDED HEART RATE VARIABILITY PARAMETERS (ACCORDING TO [31])

Heart rate variability measure	Definition and explanation	Indicator of	Activity as part of the autonomic nervous system
SDNN	Standard deviation of NN-intervals: Standard deviation of NN-intervals in the measurement time range	Overall variability	No clear allocation
RMSSD	Root Mean Square of successive differences: Square root of the arithmetic mean of squared differences between adjacent NN intervals	Short term variability	Parasympathetic
LF	Low frequency power: Power density spectrum in the frequency range from 0.04 to 0.15 Hz	No clear allocation	Sympathetic and parasympathetic nervous system, the sympathetic nervous system predominates.
HF	High frequency power: Power density spectrum in the frequency range from 0.15 to 0.40 Hz	Short term variability	Parasympathetic

G. Statistical Analysis

A repeated measures ANOVA was conducted to test the main and the secondary hypothesis. The comparison was made based on the logarithmic values in order to catch outliers. Statistical significance was assumed when $p < 0.05$. Statistical tests were performed with Jamovi 2.3.21.

III. RESULTS

A. Main Factor

There are some indications of changes in HRV due to EMF exposure. Table IV shows significant effects on SDNN in run 1, run 2 and run 3. Beyond that, significant effects are only evident in run 1, for the characteristics RMSSD, LF and HF. For SDNN, a highly significant decrease from OFF 1 to ON and a significant difference between OFF 1 and OFF 2 can be seen in run 1 and run 3. In run 2, a significant increase in SDNN from ON to OFF 2 can be read. For run 1, there are also effects between OFF1 and ON for the features RMSSD, LF, and HF. For run 2 and 3, differences are only evident for the feature SDNN. The observed changes of SDNN from OFF1 to ON (decrease) and from ON to OFF 2 (increase) are in line with the hypotheses. The fact that there are also significant differences between OFF 1 and OFF 2 can be interpreted in such a way that the SDNN normalization takes longer than 10 minutes after exposure.

Fig. 3 gives an overview of the SDNN mean values at the three measurement times of all three runs. It can be seen that run 1 and run 3 have a similar course. In all three runs, a decrease in the SDNN value (from OFF1 to ON) is followed by an increase (from ON to OFF2) after the end of exposure.

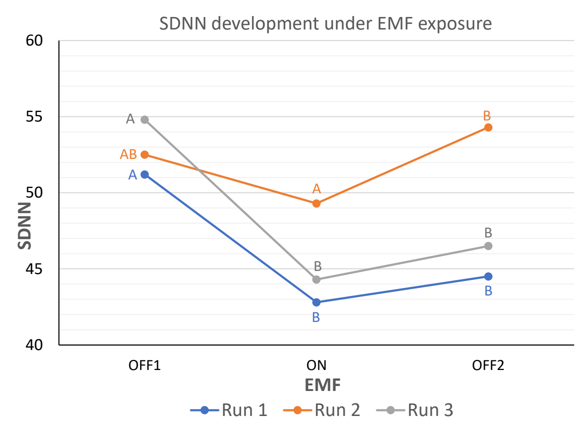

Fig. 3. SDNN measurement at three different stages (OFF1, ON, OFF2). Mean values run 1 (60 observers), run 2 (54 observers) run 3 (40 observers). Deviating letters show significant differences; alpha = 0.05.

B. Cofactors

We were interested in whether consumption of caffeine-containing beverages (especially coffee), smoking and the use of medication altered the observed pattern. Here, the use of strong medications was recorded - medications for chronic diseases under medical supervision that interfere with cardiac function.

These three factors were examined separately. Table V shows that all groups, coffee consumption, medication and smoking, respond significantly to RF-EMF. The factors of smoking, medication and coffee do not differ from their comparison groups. This implies that the EMF impact is not influenced by the following factors: coffee consumption, smoking and medication. Fig. 4 illustrates that the patterns change only slightly compared to the control groups. The SDNN values decrease from phase OFF1 to phase ON and increase again in phase OFF2, but do not reach the level of phase 1 OFF1. Only the medication group shows no increase in the HRV parameter SDNN from ON to OFF2 after 10 minutes. It is possible that recovery is slowed down.

TABLE IV. EFFECTS OF EMF EXPOSURE ON HRV PARAMETERS. DESCRIPTIVE STATISTICS REPEATED MEASURES ANOVA OF HRV PARAMETERS. BOLD INDICATES SIGNIFICANT DIFFERENCES

HRV parameters	**Descriptive statistics**				**Repeated measures ANOVA**		
		phase			Post- Hoc	*p-value*	Effect size Cohen´s d
		OFF1	*ON*	*OFF2*			
SDNN run 1	No. of observations	60	60	60	OFF1-ON	**< .001**	0.58
	Mean	51.23	42.78	44.55	ON-OFF2	0.065	0.24
	Standard deviation	35.65	25.13	25.08	OFF1-OFF2	**0.011**	0.37
SDNN run 2	No. of observations	54	54	54	OFF1-ON	0.35	0.19
	Mean	52.5	49.33	54.28	ON-OFF2	**0.026**	0.37
	Standard deviation	27.1	25.01	27.2	OFF1-OFF	0.405	0.11
SDNN run 3	No. of observations	40	40	40	OFF1-ON	**0.002**	0.57
	Mean	54.75	44.25	46.48	ON-OFF2	0.139	0.24
	Standard deviation	32.52	26.08	28.02	OFF1-OFF2	**0.035**	0.39
RMSSD run 1	No. of observations	60	60	60	OFF1-ON	0.124	0.27
	Mean	34.47	31.85	32.47	ON-OFF2	0.176	0.22
	Standard deviation	25.41	24.70	24.44	OFF1-OFF2	0.264	0.15
RMSSD run 2	No. of observations	54	54	54	OFF1-ON	0.446	0.1
	Mean	38.52	38.24	39.30	ON-OFF2	0.313	0.2
	Standard deviation	28.86	28.10	25.83	OFF1-OFF2	0.276	0.23
RMSSD run 3	No. of observations	40	40	40	OFF1-ON	0.410	0.21
	Mean	39.23	32.03	33.53	ON-OFF2	0.410	0.24
	Standard deviation	41.85	25.25	26.19	OFF1-OFF2	0.659	0.07
LF run 1	No. of observations	60	60	60	OFF1-ON	**0.023**	0.36
	Mean	0.12	0.11	0.11	ON-OFF2	0.339	0.12
	Standard deviation	0.06	0.07	0.07	OFF1-OFF2	0.094	0.26
LF run 2	No. of observations	54	54	54	OFF1-ON	0.970	0.09
	Mean	0.12	0.12	0.12	ON-OFF2	0.970	0.1
	Standard deviation	0.07	0.06	0.07	OFF1-OFF2	0.853	0.15
LF run 3	No. of observations	40	40	40	OFF1-ON	0.690	0.15
	Mean	1	0.96	1	ON-OFF2	0.605	0.21
	Standard deviation	0.37	0.36	0.32	OFF1-OFF2	0.770	0.05
HF run 1	No. of observations	60	60	60	OFF1-ON	**0.030**	0.34
	Mean	0.14	0.12	0.12	ON-OFF2	0.945	0.01
	Standard deviation	0.09	0.09	0.09	OFF1-OFF2	**0.030**	0.34
HF run 2	No. of observations	54	54	54	OFF1-ON	1.000	0.07
	Mean	0.15	0.15	0.16	ON-OFF2	1.000	0.08
	Standard deviation	0.11	0.1	0.1	OFF1-OFF2	1.000	0.12
HF run 3	No. of observations	40	40	40	OFF1-ON	0.254	0.28
	Mean	0.15	0.13	0.13	ON-OFF2	0.586	0.09
	Standard deviation	0.14	0.11	0.10	OFF1-OFF2	0.486	0.19

TABLE V. WITHIN-SUBJECTS-EFFECTS OF COFFEE CONSUMPTION, SMOKING AND MEDICATION. SPHERICITY CORRECTION ACCORDING TO GREENHOUSE-GEISSER

Within Subjects Effects	Sum of Squares	df	Mean Square	F	p	η^2_p
Coffee						
EMF	0.77	1.46	0.53	8.21	**0.002**	0,13
EMF ✻ groups	0.11	1.46	0.08	1.21	0.29	0,02
Residues	5.26	81.9	0.06			
Medication						
EMF	0.75	1,44	0.52	7.62	**0.003**	0,12
EMF ✻ groups	0.02	1.44	0.01	0.18	0.77	0,003
Residues	5.57	81.9	0.07			
Smoking						
EMF	1.06	1.45	0.73	10.9	**< .001**	0.16
EMF ✻ groups	0.02	1.45	0.02	0.3	0.71	0.004
Residues	5.59	83.3	0.07			

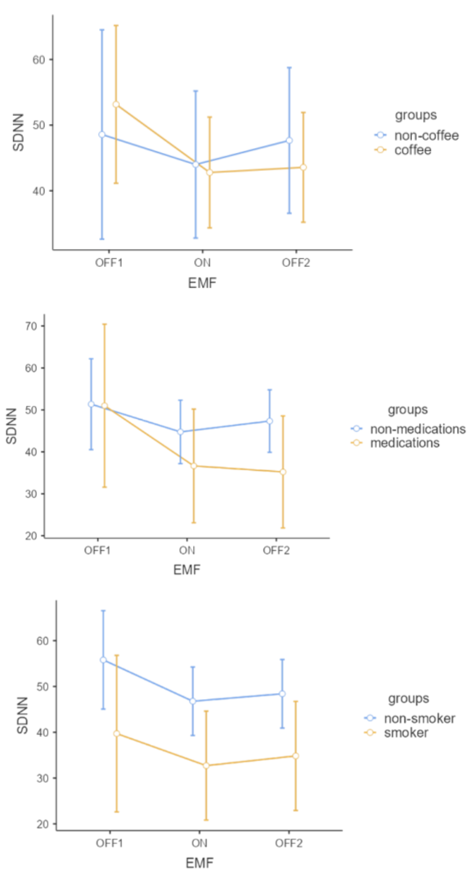

Fig. 4. SDNN measurement at three time points (OFF1, ON, OFF2). Mean values and confidence intervals. Figure above: comparison of the groups: coffee (n=37) and non-coffee (n=21), figure in the middle: comparison of the groups medication (n=14) and non-medication (n=45), figure below: comparison of the groups smoker (n=17) and non-smoker (n=43).

IV. DISCUSSION

In our experiments the HRV response follows the same pattern: a decrease due to RF-EMF exposure and an increase after the exposure is over. In run 1 and 3, the SDNN value decreased significantly with the onset of radiation. In run 2, the SDNN value increased significantly after the termination of radiation. These results are consistent with the main hypothesis that RF-EMF lowers HRV.

Numerous factors influencing HRV have already been investigated [31]. A lowering of HRV has been observed in various types of stress [14, 15].

Under our experimental conditions, SDNN responds most to RF-EMF exposure compared to RMSSD, LF and HF. SDNN describes the overall variability of HRV [31], while the other characteristics considered describe other HRV aspects. Even in the study by Parazzini et al. (2007), only a few HRV parameters responded significantly, including SDNN. There was a decrease in variability as a result of exposure. Future research should further investigate which HRV parameters are suitable for measuring RF-EMF effects under various conditions (e.g. frequencies and power flux density).

It is also noticeable that in run 2 the differences between phase OFF1 and phase ON were smaller and not significant. Run 2 was performed in late May and June with high outdoor temperatures, which is why the temperatures in the laboratory also increased, often, up to 30 degrees Celsius. By contrast, run 1 and run 3 were performed at comparably low outdoor temperatures in March-April and October-November, with room temperatures around 20 degrees Celsius. The influence of heat and cold on HRV has been studied [32, 33]. High temperatures are reported to reduce HRV. It is to be clarified in future research whether the responsiveness to RF-EMF is lowered by high temperatures.

Participants' consumption of caffeine-containing beverages, smoking, and use of strong medications were recorded – medications for chronic diseases under medical subscription, intervening in heart functioning. Examination of the three factors showed that the effect of RF-EMF was also observed for the groups with coffee consumption, smoking and the intake of medication. There were no significant differences between subgroups, for example, smokers and non-smokers. However, the HRV level of smokers was at a lower level. An HRV-lowering effect of smoking is also described by [34, 35].

Several studies have described effects of EMF on cardiac response, in humans and in animals [26, 36, and 37]. In contrast, some studies show no significant effects of short-term radiation on the cardiovascular system [38, 39]. The effects of Wi-Fi frequencies on HRV have hardly been studied so far. Parizek et al. (2023) [17] found a marked shift in autonomic regulation of heart rate toward complex sympathetic overactivity by Wi-Fi and decreased parasympathetic activity by 4G radiation when healthy young subjects were exposed to 2400 (Wi-Fi) and 2600 MHz (4 G) for five minutes each. It seems necessary to take a close look at the studied EMF factor. In our case we wanted to simulate an office environment. The frequencies used were DECT (1.8 GHz) and Wi-Fi (2.45 GHz). The devices were about 1 m apart. The power flux density was 16 000 µW/m^2

(peak value) resp. 110 µW/m² (RMS). The power flux density corresponds to values also documented in the literature [40]. In the review [40], the authors determine a maximum mean exposure for offices of 3.447 mW/m². A research by study [41] of peak RF-EMF emissions in typical office environments showed a peak power density of 54 mW/m².

In the meantime, however, significantly higher values can already be detected outside. In the 2022 study by [36], measurements were made in areas of Stockholm where clusters of EMF emitters were placed at low heights (near the head area) of pedestrians. The maximum measured mean value, reached a power flux density of 12.1 V/m (388 mW/m²). The highest measured value on the whole surveyed area was 31.6 V/m (2 648 mW/m²).

In our experiment, with a short exposure of 10 minutes, EMF effects on HRV were found even though the power flux density was only 0.000275% of the ICNRIP limit [6] (ICNIRP 2020 Guidelines).

V. Conclusion

HRV seems to be a relatively simple method of measuring EMF effects on humans under certain conditions. There are questions about the optimization of the experimental design: In further studies, the duration of the exposure should be varied because an exposure time of 10 minutes seems to be low or not realistic. On the other hand, the control situation in experiments needs to be carefully considered, as sites with very low radiation become rarer. It is also to be examined in the future whether, as with smoking, a permanent lowering of HRV occurs through RF-EMF.

There are recent studies indicating 5G will contribute with a significant proportion of radiofrequency exposure in the future [42–44, 44–46]. In this respect, 5G frequencies are to be added in the future to investigate the effects of EMF on HRV.

Authors' Contribution

Conceptualization: J.U.G. and S.D.; methodology: J.U.G., S.D. and R.R.; software: R.R.; formal analysis: J.K.; investigation: S.D, R.R., S.P., A.A-D.; writing—original draft preparation: S.D., R.R. and J.U.G.; writing—review and editing: S.D., J.K. and J.U.G. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was approved by the Research Ethical Committee of the University of Oradea (the decision was registered at the Research Programs and Projects Office with nr. 660/5.11.2020).

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study. All participants signed a written informed consent before they took part voluntarily in the study. Each member of the implementation research team signed a confidentiality declaration regarding the participants' data.

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Conflicts of Interest

The authors declare no conflict of interest.

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