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NEUROVEGETATIVE DISTURBANCES IN WORKERS EXPOSED TO 50 Hz ELECTROMAGNETIC FIELDS

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Abstract
Objectives: Since the circulatory and nervous systems are composed of electrically excitable tissues, it is plausible that they can be stimulated by electromagnetic fields (EMF). No clinical studies have as yet been carried out to explain whether and how occupational exposure to 50 Hz EMF can influence the neurovegetative regulation of the cardiovascular function. The present project was undertaken to assess the autonomic function in workers occupationally exposed to 50 Hz EMF, by analyzing the heart rate variability. **Materials and Methods:** The study group comprised 63 workers of switchyard substations, aged 22–67 years (39.2 ± 10.0 years), and the control group 42 workers of radio link stations, aged 20–68 years (40.7 ± 9.2 years), employed at workposts free from EMF exposure. The age range and employment duration in both groups did not differ significantly. To assess the neurovegetative regulation of the cardiac function, heart rate variability (HRV) analysis was made based on 512 normal heart beats recorded at rest. The analysis, performed using fast Fourier transformation, concerned the time- and frequency-domain HRV parameters. Power spectrum in the very low (VLF), low (LF) and high (HF) frequency bands was determined. **Results:** The relative risk of decreased HRV (STD R-R < 27 ms), calculated with use of a logistic regression model, was significantly higher in the exposed group than in controls (OR = 2.8). The VLF power spectrum was significantly higher in the exposed group and correlated with the exposure level. The percentage of subjects with dominant sympathetic function (LF/HF>1) was significantly higher in the study group than in controls (65% vs. 47%). **Conclusions:** It was concluded that occupational exposure to 50 Hz EMF could influence the neurovegetative regulation of the cardiovascular system.

Key words:
Autonomic nervous system, Heart rate variability, Power frequency electromagnetic fields

INTRODUCTION

Power frequency (50/60 Hz) electromagnetic field (EMF) surrounds the generators and transmitters of electric current as well as any current-powered device or equipment. As a consequence, virtually everybody is exposed to such fields. It is thus essential to elucidate the biological mechanism of action and assess possible health effects of exposure in humans.

The direct effect of EMF exposure is thought to be associated with the stimulation of electrically excitable tissue and it seems to largely depend on EMF intensity. Since the circulatory and nervous systems are composed of electrically excitable tissues, it is plausible that they can be stimulated by electromagnetic fields. However, this would require a very high intensity of the current. The threshold value of current density at which stimulation of excitable tissues has been observed is about 100 mA/m^2 (ventricular fibrillation may be caused by densities as high as 1000 mA/m^2) [1], but such values are rarely encountered in an occupational setting**.** The pathomechanics and possible health effects of exposure to

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EMF generated by low density current have not been sufficiently clarified. Neither experimental nor clinical investigations conducted in several countries have explained whether and how weak, 50Hz, EMF can have impact on the cardiovascular system or its neurovegetative regulation. Human volunteer studies provide contradictory findings. Some have indicated bradycardia as one of the cardiac effects of exposure to weak power frequency EMF [2–4]; whereas others do not report any significant cardiovascular abnormalities [5–8]. In some studies, dysfunction of the autonomic nervous system [9], arterial blood pressure (hypo- or hypertension), heart rhythm (brady- or tachycardia) disturbances [10,11] and an increased neuromuscular activity [12] were found in workers occupationally exposed to 50/60 Hz EMF. Other investigations [9,11,13–16] did not confirm these findings. In many cases, arriving at conclusions was difficult due to the lack of data on exposure levels, concomitant exposure to other occupational or environmental hazards or the lack of a well-matched control group.

In view of the above and the fact that no reports containing such data are available in literature, we have undertaken a study to assess the cardiovascular function and its neurovegetative regulation in workers exposed to 50 Hz electromagnetic fields. To this end, we analyzed heart rate variability (HRV), a sensitive indicator, which allows to assess autonomic regulation.

MATERIALS AND METHODS

Subjects

The exposed group comprised 63 male technical service workers of four switch-yard substations who had been qualified by an occupational health physicians as fit for work at permissible EMF levels. The subjects' age ranged from 22–67 years and their employment duration from 1 to 41 years. Substations are an element of the power system in which electric power is distributed and/or transformed, and their equipment is a source of 50 Hz electric and magnetic fields. The substations under study operated at high and extra high voltage (110–400 kV) and the maximum values of magnetic fields were 26.1–37.3 μT, and of electric fields 4.3–6.7 kV/m, whereas admissible values for the whole 8-h work shift, according to Polish hygiene standards, are 200 A/m (about 250 μT) and 10 kV/m, respectively.

The control group consisted of 42 male technical service workers of four radio link stations, aged 20–68 years. Radio link stations constitute an element of the telecommunication system in which signals are transmitted using EM waves focused into very row beams by directional (mostly parabolic) antennas. As the antennas are installed in highly inaccessible locations and the radiation beams run high above the ground, the workers of the radio link stations are free from EMF exposure.

The workers in both the study and control groups were employed according to a 4-day working scheme: a 12-h shift (daytime) – a 24-h rest and a 12-h shift (night-time) – a 48-h rest. The two groups were similar with respect to the level of education, physical fitness as well as dietary and smoking habits (Table 1). The substations and radio link stations were selected randomly.

The study protocol was approved by the Regional Biomedical Ethics Committee. Before the examinations, all the procedures were fully explained to the workers. All subjects eligible for the study gave informed consent prior to their inclusion in the study. All workers from each station were examined.

Table 1. Characteristics of the study population

Variables	Switch-yard substations (Study group)	Radio link stations (Control group)
Number of subjects	63	42
Age (years)	39.2 ± 9.9	40.7 ± 2.2
Employment (years)	14.9 ± 10.3	12.9 ± 4.0
Body mass index (BMI)[a]	26 ± 4	25 ± 4
No. of smokers (more than 10 cigarettes a day)	21 (33%)	16 (38%)
EMF exposure: frequency (Hz)	50	0
E_{max} (kV/m)	4.3–6.7	0
B_{max} (μT)	26.1–37.3	0
E_{dose} (kV/m)h	0.2–15.2	0
B_{dose} (μT)	1.4–38.9	0

[a] BMI – body mass/height^2 (kg/m^2).

Medical examinations

The workers were subjected to:

- general medical examinations combined with an interview, including family history of metabolic and cardiovascular diseases, lifestyle factors, nutritional habits and physical activity,
- electrocardiological (ECG) examinations: resting ECG with late ventricular potentials (LVP) and heart rate variability (HRV) analyses, 24-h ECG and ambulatory blood pressure (ABP) monitoring. Detailed results of 24-h ECG and ABP monitoring were reported in our previous paper [17].

Evaluation of heart rate variability

Heart rate variability was assessed based on 512 consecutive, normal cardiac cycles, recorded at rest. The recording equipment included Medea-HRV computer system (Gliwice-Poland) consisting of a three-channel low-noise biological amplifier, a 16 bit AD digitizer and IBM PC 486/33 MHz. ECG signal was sampled at a rate of 2000 samples per sec. and filtered to remove ectopic activity and artefacts prior to R-R interval file generation. Digital conversion of signals comprised the registration of ECG signals, preliminary conversion and final conversion. The system is characterized by a high accuracy of QRS detection with a precise determination of fiducial points for QRS complexes and P and T waves. Then, the duration of the focused ECG signal was averaged and the R-R, P-R and R-T intervals were established. The software for ECG record analysis makes use of the sequence of P-R, R-R and R-T segments marked by the fiducial points and enables the statistical and spectral analysis of R-R variability.

Time-domain HRV analysis made it possible to calculate the following parameters: mean R-R interval (AVG R-R); R-R standard deviation (STD R-R) median, modal, minimum and maximum R-R values. Some authors postulate that the STD R-R values of more than 25 or 30 ms should be considered normal [18]. Based on our own experience, we adopted 27 ms as the threshold value.

For spectral analysis, the intervals were sampled again after Berger (5 Hz) and after windowing (Blackman-Harris window), the power spectral density (an area covered by the power spectrum) was calculated with the fast Fourier transform (FFT) for the following frequency bands: very low (VLF): 0.0167–0.05 Hz; low (LF): 0.05–0.15 Hz; high (HF): 0.15–0.35 Hz, and expressed as percentage of power spectrum in the range of 0.0–2.5 Hz. Moreover, power spectrum over the range of 0 to 0.5 Hz and the LF/HF ratio were calculated.

According to the commonly adopted interpretation, the high-frequency power spectrum is parasympathetic-mediated, while the low frequency sympathetic/parasympathetic-mediated [19]. The LF/HF ratio indicates sympathovagal balance. LF/HF > 1 shows the prevalence of sympathetic activity in the neurovegetative regulation of the cardiovascular system [19].

ECG signal was recorded using XYZ orthogonal leads, according to Frank, after a 10-min rest in a lying position. Since HRV parameters differ widely, depending on the time of the day, daily diet or specific stimulating foods consumed, and the medications taken by the subjects, the study was performed under standardized conditions. The subjects were examined in the morning hours following normal night rest, before or 2 h after a light meal; they could not have coffee, tea, or alcohol and had to refrain from smoking before the examination. None of them took any medications that could affect the activity of the autonomic nervous system (e.g., beta-blockers) [18,19].

Exposure evaluation

Exposure to 50 Hz electric and magnetic fields was assessed by measuring maximum values of the electric field strength (E_{max}), magnetic flux density (B_{max}) and the EMF daily doses (E_{dose}, B_{dose}). The EMF daily dose was determined using a quasi-dosimetric method based on an interview and detailed work timing for each worker and measurements in several locations at the substation. The results of these partial measurements were then averaged for the whole area of the substation.

To measure electric field intensity, a broadband MEH-1a meter (Technical University of Wrocław, Poland) with AE-43 probe (three orthogonal electric dipoles) was applied. This set provides valid measurements of 50 Hz – 50 kHz fields in the 0.2–20 kV/m range with ± 10% accuracy for free space and ± 3 dB accuracy for a 10 cm distance from primary and secondary EMF sources. Magnetic field intensity was measured using MNP89 meter (Technical University of Wrocław, Poland) with a directional probe, which provides for measurements in the 0.01 A/m – 20 kA/m range, with ±10% accuracy. The H value was determined for three orthogonal planes and then the resultant was calculated. The measuring equipment was calibrated at the Technical University of Wrocław, Poland.

Statistical analysis

The differences between the control and exposed groups were analyzed using the chi-square or Fisher's exact test for contingency table, e.g., for HRV abnormalities (R-R < 27 ms), and Student's t-test for normally distributed variables or the non-parametric Mann-Whitney test for other distributions. The analysis of variance with multiple comparison tests was used to compare the mean values of variables in the study and control groups. A logistic regression model was used to estimate the risk of HRV abnormalities in relation to particular co-factors, such as age, number of cigarettes smoked, duration of employment, exposure level, and the level of work-related stress assessed according to the Cohen Questionnaire. The multiple linear regression allowed analyzing the relationship between HRV parameters and the period of work under exposure and exposure level.

RESULTS

In EMF-exposed workers, the mean R-R value (AVG R-R) and standard deviation (STD R-R) were lower than in the control group, however, the difference was not statistically significant. The time-domain HRV parameters are displayed in Table 2.

Fifteen (24%) workers in the study group, and four (10%) controls, showed STD R-R lower than 27 ms (Table 2). In the study group, the relative risk of lowered HRV, adjusted for age, smoking and drinking habits, was about three times as high as in controls (OR = 2.8). Also in this group, of the 15 subjects with decreased HRV, 8 showed abnormalities in 24-h ECG records, 4 had changes in resting ECG, and 3 had late ventricular potentials. One person showed parallel abnormalities: decreased HRV, LVPs and changes in 24-h ECG monitoring. In the control group, of the four people with decreased HRV, only one subject presented abnormal resting ECG records.

The analysis of R-R power spectrum density by FFT showed that the total power spectral density (TPSc) in the exposed workers and controls did not differ significantly

Table 2. Time-domain heart rate variability (HRV) parameters

Groups	STD R-R <27 ms	AVG R-R (ms)	STD R-R (ms)	Median (ms)	Modal (ms)	Minimum (ms)	Maximum (ms)
Study	24%	845.4 ± 156.9	46.2 ± 25.9	847.2 ± 158.2	843.8 ± 160.5	704.0 ± 136.3	994.1 ± 192.3
P	< 0.05	NS	NS	NS	NS	NS	NS
Control	10%	864.1 ± 126.4	62.9 ± 53.5	867.5 ± 128.3	859.8 ± 132.5	687.7 ±123.5	1031.3 ± 149.3

NS – non-significant difference (P>0.05); STD R-R <27 ms – percentage of people with lowered STD R-R; AVG R-R – mean R-R interval.

Table 3. Frequency-domain parameters of heart rate variability (HRV) parametres

Groups	Power in bands (%)					
	LF/HF>1	VLF	LF	HF	TPSc	LF/HF
Exposed group	65%	13.8 ± 5.4	27.5 ± 7.6	24.6 ± 6.5	73.2 ± 7.4	1.0 ± 0.5
P	< 0.05	0.011	NS	NS	NS	NS
Control group	47%	11.2 ± 4.8	24.4 ± 9.3	25.4 ± 7.3	71.2 ± 9.0	1.2 ± 0.5

LF/HF > 1 – percentage of workers with dominant sympathetic activity; LF – (MWSA - Mayer wave); power spectrum within low frequency range (0.05–0.15 Hz); VLF – power spectrum within very low frequency range, below 0.05 Hz; HF – (RSA – respiratory peak); power spectrum within high frequency range (0.15–0.35 Hz); TPSc – total power spectrum within 0.0–0.5 Hz band; LF/HF – sympathovagal balance ratio.

Table 4. Blood pressure and heart rate in the exposed and control groups

Parameters	Study group	Control group	P
BPSD	132.0 ± 14.1	125.7 ± 12.1	0.032
BPDD	79.4 ± 8.9	75.8 ± 9.8	NS
BPSO	129.2 ± 14.0	122.0 ± 11.9	0.014
BPDO	77.6 ± 9.3	73.2 ± 9.3	0.041
BPSN	117.3 ± 17.6	106.7 ± 12.2	0.002
BPDN	68.2 ± 11.9	62.5 ± 7.4	0.01
BPSD/BPSN	1.14 ± 0.1	1.18 ± 0.1	NS
BPDD/BPDN	1.18 ± 0.1	1.22 ± 0.1	NS

BPSD – systolic blood pressure during day;
BPSO – systolic blood pressure during 24 h;
BPDD – diastolic blood pressure during day;
BPDO – diastolic blood pressure during 24 h;
BPSN – systolic blood pressure during night;
BPDN – diastolic blood pressure during night.

(Table 3). However, the VLF power spectrum density was significantly higher in those exposed than in controls. A statistically significant correlation was found between the VLF power spectrum and 24-h mean values of systolic and diastolic blood pressure (BP). The data on arterial blood pressure revealed a significantly higher systolic BP in the exposed workers not only during daytime, but also at night, and higher diastolic BP at night (Table 4). We found that in the study group, the percentage of subjects with elevated BP was significantly higher (P = 0.04) compared with controls (38% vs. 23%).

In the exposed workers, HF and LF power spectral densities were lower than in controls, but the findings were of no

Table 5. Characteristics of the exposed subgroups, divided according to E_{dose} and B_{dose}, and the control group

Variables	Groups				P
	Control	Study			
		I	II	III	
E_{dose} (kV/m)h	0	0.2–0.6	1.3–2.4	11.0–15.2	
B_{dose} (μT)		1.4–2.5	8.9–12.8	25.1–38.9	
No. of subjects	42	13	24	26	
Age (years)	40.7 ± 14.0	37.7 ± 11.7	40.5 ± 9.3	38.7 ± 9.7	NS
Employment duration (years)	16.7 ± 13.2	11.7 ± 10.6	15.4 ± 9.9	16.0 ± 10.5	NS
BMI (kg/m^2)	25.4 ± 4.1	27.2 ± 3.2	25.4 ± 3.3	26.3 ± 4.0	NS
Percentage of smokers (>10 cigarettes/ day)	38%	46%	33%	52%	NS

BMI – body mass/height^2 (kg/m^2).

Table 6. Selected parameters characterizing heart rate variability in relation to exposure level

Variables	Groups				P
	Control	Study			
		I	II	III	
E_{dose} (kV/m)h	0	0.2–0.6	1.3–2.4	11.0–15.2	
No. of subjects	42	13	24	26	
AVG R-R	864.1 ± 126.4	864.9 ± 160.7	848.2 ± 160.9	825.2 ± 154.4	NS
STD R-R	62.9 ± 53.5	51.6 ± 27.2	46.2 ± 27.7	44.2 ± 24.4	NS
VLF	11.2 ± 4.8	13.6 ± 5.7	12.5 ± 4.8	15.2 ± 5.7	0.026 0–III
LF	24.4 ± 9.3	27.9 ± 8.2	27.5 ± 8.4	27.1 ± 6.8	NS
HF	25.4 ± 7.3	24.5 ± 7.3	24.9 ± 5.9	24.5 ± 7.5	NS
TPSc	71.2 ± 9.0	74.0 ± 6.9	72.2 ± 8.1	73.6 ± 7.4	NS
LF/HF	1.0 ± 0.54	1.23 ± 0.47	1.16 ± 0.40	1.20 ± 0.60	NS

AVG R-R – mean R-R interval; STD R-R – standard deviation R-R;
LF – power spectrum within low frequency range (0.05–0.15 Hz);
TPSc – total power spectrum within 0.0–0.5 Hz band;
NS – non-significant differences.
VLF – power spectrum within very low frequency range, below 0.05 Hz;
HF – power spectrum within high frequency range (0.15–0.35 Hz);
LF/HF – sympathovagal balance ratio;

statistical significance. The LF/HF ratio did not differ significantly between the study and the control groups. However, the former comprised a significantly higher percentage of subjects with LF/HF > 1 (65% and 47%, respectively).

Analysis of correlation between heart rate variability and exposure parameters

The multiple linear regression did not show any statistically significant correlation between HRV parameters and duration of employment under exposure and exposure level.

At the next stage of the analysis, the study group was divided into subgroups (I, II, III) according to the E_{dose} and B_{dose} values, and according to the E_{max}, and B_{max} values. The comparison of HRV parameters in subgroups selected according to E_{max} and B_{max} did not show significant differences. Therefore, we omitted these results in the present paper.

The characteristics of the E_{dose} and B_{dose} subgroups are presented in Table 5. These subgroups did not differ significantly with respect to the age, duration of employment, BMI, and smoking habit. HRV analysis in each subgroup demonstrated that the time-domain parameters did not change significantly with increasing exposure (Table 6). Among the frequency-domain HRV parameters, only the power spectrum density of VLF increased with increasing exposure. As evidenced by the analysis of discrete variables, the percentage of subjects with lowered HRV was significantly higher ($p = 0.029$) in subgroups II (25%) and III (32 %) than in the control group (10%).

DISCUSSION

The findings on the time-domain HRV parameters indicated that in the exposed group HRV expressed as STD R-R was lower while the resting heart rate (lower AVG R-R) was higher in comparison with the control group. These differences intensified with the increasing exposure level. Faster heart rate (HR) is an undesirable symptom. A number of prospective studies performed in different countries demonstrated that people with increased HR are at a higher risk for coronary heart disease (CHD) and the related mortality than people with a slower pulse [20–25].

In the present study, a strong, positive relationship was found between HRV and both systolic and diastolic BP [26]. Also, the number of workers with lowered HRV in the exposed group was about three times as high as that among controls. The lowered HRV may lead to grave consequences. Prospective studies have shown that patients with heart rhythm disturbances in 24-h ECG, who also exhibit the decreased HRV, are at several times higher risk of sudden death than those with the similar ventricular arrhythmia but with normal HRV [27,28]. Although the data on the prognostic value of lowered HRV in healthy individuals are rather scarce, it seems that this abnormality may also be the risk factor in this population.

The frequency-domain parameters, which reflect the neurovegetative regulation of the cardiovascular system, indicated that only VLF power spectrum density was significantly higher in the exposed group than in controls. Some authors question the applicability of evaluating VLF in short-term ECG records [29], while others consider such an assessment as valuable and reliable as that from 24-h records [30]. Little is known about the role of the VLF component in the neurovegetative regulation. It is believed that it is under the influence of both parts of the autonomic nervous system, but it is also related to the thermoregulation processes and blood pressure regulation [31,32]. Our study confirms an important role of VLF component in the BP control. Activation of the sympathetic system may be another possible mechanism of elevated BP in the exposed subjects [33]. Although no significant increase in LF power spectrum (modulated by the sympathetic system) was observed in the exposed group, the percentage of individuals with prevalent influence of the LF component (LF/HF > 1) in this group was significantly higher than in controls. Moreover, in the exposed group, the negative correlation was found between HF power spectrum (modulated by the parasympathetic system) and 24-h systolic and diastolic BP. The prevalence of the sympathetic regulation and the decreased protection of the heart by the parasympathetic system create preconditions not only for arterial hypertension but also for the occurrence of heart rhythm disturbances and the development of coronary heart disease [34,35]. Owing to methodological differences, it is difficult to compare our findings on neurovegetative control in workers exposed to 50 Hz EMF with relevant literature data. However, numerous authors reported dysfunction of the autonomic nervous system in EMF exposed individuals [9–11]. The function of the autonomic nervous system has been assessed either by employing traditional tests (Valsalva manoeuvre, deep breathing test, orthostatic test, and isometric handgrip test), or by determining the level of catecholamines (adrenaline, noradrenaline, and dopamine). A recent investigation by Sastre et al. [36] who used HRV analysis demonstrated that intermittent exposure to 60 Hz magnetic fields under experimental conditions caused a decrease in power spectrum density in the VLF range. However, it is difficult to compare the effects of experimental exposure to a relatively high-level of EMF with the consequences of long-term occupational exposure, but it seems important that in both cases changes occur in the VLF power spectrum. According to our previous study, changes in the VLF power spectrum were characteristic not only of people exposed to 50/60 Hz EMF, but also occurred in subjects exposed to medium frequency EMF [37].

Our investigations indicate the occurrence of changes in neurovegetative regulation in the exposed subjects correlated with a significant increase in mean values of arterial blood pressure and more frequent incidents of hypertension [17]. Other authors also suggested that the disturbed neurovegetative regulation might have caused changes in arterial blood pressure of people exposed to power frequency (50/60 Hz) EMF. However, there were controversies about the direction of these changes since either increase or decrease in blood pressure linked with the exposure was observed [11].

CONCLUSIONS

In the examined workers occupationally exposed to 50 Hz electromagnetic fields, the risk of neurovegetative disturbances was significantly increased, although the level of exposure in their occupational setting did not exceed admissible values. The most prevalent cardiovascular abnormality was a significantly increased arterial blood pressure accompanied by a significant increase in VLF power spectral density. A remarkable fact was also that the percentage of individuals with sympathetic nervous system predominance in cardiovascular regulation was significantly higher in the exposed than in the control group (65% vs. 47%).

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