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Autonomic Neuroscience: Basic and Clinical 105 (2003) 53–61

AUTONOMIC NEUROSCIENCE: Basic & Clinical

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Can extremely low frequency alternating magnetic fields modulate heart rate or its variability in humans?

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Received 24 June 2002; received in revised form 29 October 2002; accepted 17 December 2002

Abstract

This study is a reexamination of the possibility that exposure to extremely low frequency alternating magnetic field (ELF-MF) may influence heart rate (HR) or its variability (HRV) in humans. In a wooden room (cube with 2.7-m sides) surrounded with wire, three series of experiments were performed on 50 healthy volunteers, who were exposed to MFs at frequencies ranging from 50 to 1000 Hz and with flux densities ranging from 20 to 100 μT for periods ranging from 2 min to 12 h. In each experiment, six indices of HR/HRV were calculated from the RR intervals (RRIs): average RRI, standard deviation of RRIs, power spectral components in three frequency ranges (pVLF, pLF and pHF), and the ratio of pLF to pHF. Statistical analyses of results revealed no significant effect of ELF-MFs in any of the experiments, and suggested that the ELF-MF to which humans are exposed in their daily lives has no acute influence on the activity of the cardiovascular autonomic nervous system (ANS) that modulates the heart rate.

Keywords: Extremely low frequency magnetic field; Heart rate; Heart rate variability

1. Introduction

The autonomic nervous system (ANS) has an essential function of adapting promptly to changes in the surrounding environment. The system modifies its activity by accepting commands from the central nervous system or direct signals from the cardiovascular center in the medulla in response to physical factors such as gravity and ambient temperature. Interestingly, while most of such factors function as a sympathetic stimulator in a living system, several studies have suggested that extremely low frequency electromagnetic field (ELF-EMF), which includes power-line fields at frequency of 50 or 60 Hz and is defined as electric field (EF) or magnetic field (MF) at frequencies ranging from 0 to 3000 (Poole and Ozonoff, 1996) or 300 Hz (Repacholi and Greenebaum, 1999), may act on humans like a parasympathetic stimulator in terms of decreasing the heart rate (HR) or reducing the power of heart rate variability (HRV). In the 1990s, a group in the Midwest Research Institute (Kansas City, MO) conducted an extensive series of human experiments on the possible relationship between exposure to ELF-EMF and HR/HRV, and they observed a significant decrease in both HR and the low frequency component of the HRV power spectrum following the exposure (Cook et al., 1992; Graham et al., 1994, 2000a,b; Sastre et al., 1998, 2000). Similar experiments were performed independently by three other research groups, in which one observed changes in HR (Sait et al., 1999), while the others failed to find any HR changes (Whittington et al., 1996; Griefahn et al., 2001). If indeed ELF-EMF has such an effect, this will not only be of interest in the field of cardiophysiology but also an issue of health science because the majority of humans are almost always exposed to ELF-EMF from surrounding highly electrified environment.

Recently, one epidemiological study suggested that occupational exposure to ELF-MF may be a risk factor for death from arrhythmia-related conditions and myocardial infarction (Savitz et al., 1999), and indicated the importance of further examination of the relationship between exposure to ELF-MF and cardiovascular function.

Hence, the present study was carried out to reexamine the suggested acute effects of ELF-MF on HR/HRV by recording RR intervals (RRIs) under similar experimental conditions in a room constructed for MF exposure in humans. We used the fields that had similar characteristics to those of actual fields to which humans are exposed in their daily lives.

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doi:10.1016/S1566-0702(02)00296-5

2. Materials and methods

The present study comprised three series of experiments that differed in the mode of field and in the exposure period. These are referred to as Experiments 1 to 3 hereafter.

2.1. Facility for exposure to MF

A laboratory test facility for exposure to MF in humans was constructed at the institute based on a model of the facility built in the Midwest Research Institute (Cohen et al., 1992; Doynov et al., 1999). The facility was composed of one exposure room and another room with an MF-control system. The exposure room had a dual structure in which a small inner room (cube with 2.7-m sides) was completely enclosed by a large outer room (cube with 4-m sides). Square coils were installed in the space between the inner and outer rooms, and thus they were external and out of sight of the test environment. The walls and frames of the exposure room and the frames of surrounding coils were made of wood.

The coil design was based on the four-coil, square-loop configuration described by Merritt et al. (1983). As illustrated in Fig. 1, the four coils were composed of two outer coils with 16 turns and two inner coils with 8 turns, and the ratio of interval lengths among the four coils was 5:4:5. Such a coil design was considered to be able to generate fields with highly uniform flux densities of MFs in the inner space. The coils were set in the same manner in each of the three axes of the room. All of the windings were formed with a twisted pair of copper wires (#10 AWG, 14 twists/m), and these bifilar windings provided true active-sham exposure conditions, under which no field was generated at the same current volume when current was introduced from the opposite direction for each wire in the pair.

The room was illuminated by incandescent lamps (HNP2435, Matsushita Electric Industrial, Japan) instead of a fluorescent lamp that generates pulsed MF noise due to its inverting operation. The interior resembles a small room of a house with textured walls, provided with a small table or a bed. The exposure room was air-conditioned so that the indoor ambient temperature and relative humidity were, respectively, maintained within 1° and 5% under a constant air flow. System-related mechanical effects, such as the audible hum of vibration, perceptible change in temperature, and fluctuation of room light intensity, were suppressed as much as possible so that there existed no indication of the existence of MF to the subjects in the exposure room.

The room was not shielded from intruding magnetic fields such as static geomagnetic fields and high-frequency electric waves. The intensity of the geomagnetic field in the room was 26 μT along the horizontal axis and 31 μT along the vertical axis as determined by a three-axes flux gate sensor (MAG-03MC, Bartington Instruments, UK).

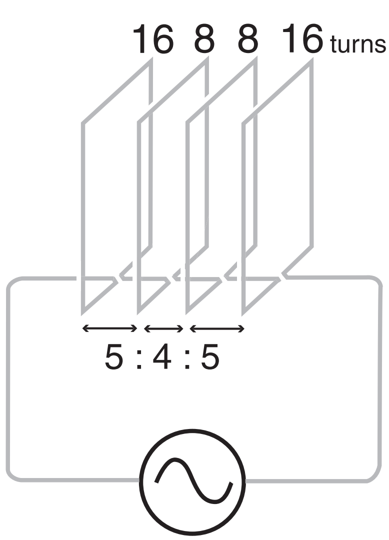

Fig. 1. Schema of coils of the facility for exposure to MFs. The actual facility had three sets of coils in *X*-, *Y*-, and *Z*-directions.

2.2. Magnetic field generation

ELF-MF is generally characterized by its frequency, intensity, polarity, and continuity. The fields existing in residential environments have a large component of power-line frequency (50/60 Hz), and the average intensity has been reported to be around 0.1 μT (Working Group for EMF-RAPID Program, 1998). In the present study, 50-Hz fields with intensities ranging from 20 to 100 μT were used. As for polarity, the fields generated near power lines have elliptic or circular polarity owing to their triple-phase transmission mode, whereas the fields originating from wires around/within houses and from electric appliances have linear polarity. Almost all of the fields near power lines and wires are continuously generated, whereas electric appliances often generate fields intermittently owing to their internal switching. The fields used in this study had two types of polarity (circular and linear), and were generated continuously or intermittently.

In the present experiment, AC signals for MFs were generated in the control room, which was next to the exposure room, using two methods as follows. In Experiments 1 and 2, signals were generated by a programming software for instrumentation (LabVIEW, National Instruments, Austin, TX) on a personal computer, and were outputted through a multichannel analog output device (AT-MIO-16E-10, National Instruments) connected to a PC. LabVIEW generated three signals corresponding to the MF on the three axes of the room separately, and outputted them in synchronized timing. In Experiment 3, AC signals were generated by an arbitrary function synthesizer (MFG 206, Micronix, Japan) corresponding to the MF on a single axis.

The polarities of the generated fields are illustrated in Fig. 2. In Experiment 1, all fields were 50 Hz and circularly polarized and had 20 kinds of modes: a combination of two modes of polarity, two modes of continuity (continuous and intermittent), and five modes of intensity (20, 40, 60, 80,

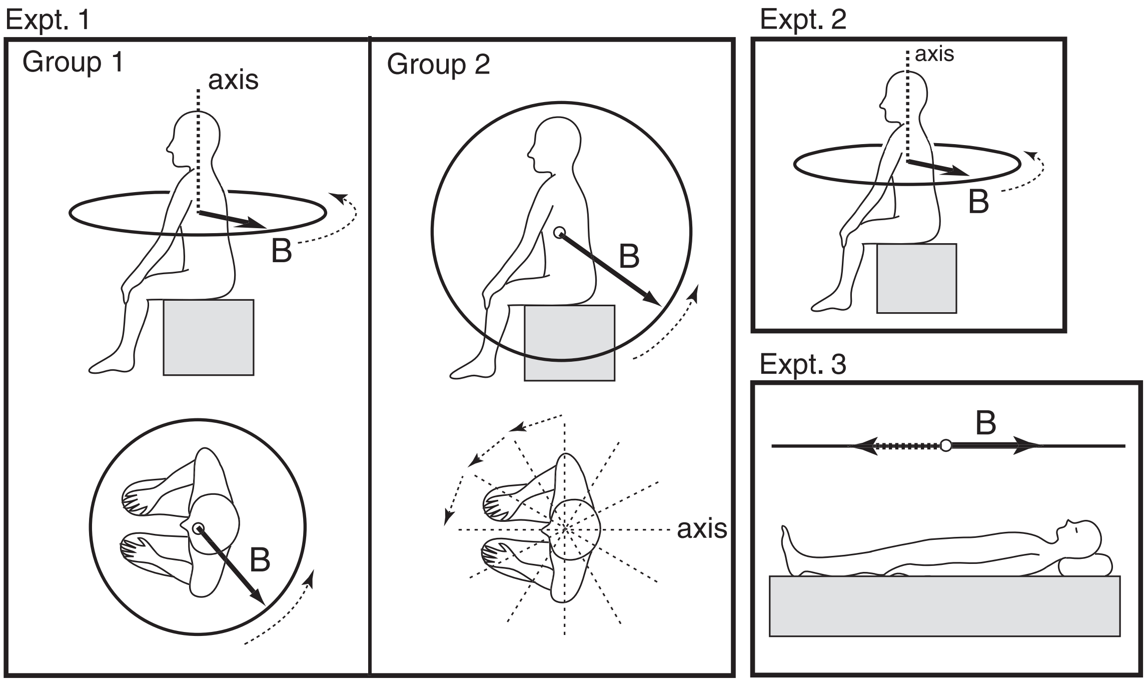

Fig. 2. Polarity of 50 Hz MFs applied in experiments. Bold arrows indicate the vector of magnetic flux (*B*), and the rotation movements of *B* or axes are indicated by dotted thin arrows. In Experiment 1, subjects were exposed to circularly polarized fields with vertical (group 1) or horizontal (group 2) axis. The field in Experiment 2 was the same as that in Experiment 1 (group 1). In Experiment 3, subjects were exposed to linearly polarized fields directed parallel to the long axis of the bed.

and 100 μT). As for polarity, the direction of the rotating axis was vertical or horizontal, and in the case of the horizontal axis, the axis itself changed direction by shifting by 30° at an interval of 1/12 s. Intermittent fields were generated by turning the fields ON or OFF every 5 s. In Experiment 2, the generated field was identical to one of those used in Experiment 1: 50 Hz/20 μT circularly polarized MF with vertical axis.

In Experiment 3, the generated field was based on a 50 Hz, 20 μT sinusoidal MF, in which three components were superimposed: third harmonics with 30% intensity of the base field, fifth harmonics with 10% intensity of the base field, and a 1-kHz, 100-μT (at the peak) field that occurred at 1-s intervals and attenuated exponentially over a duration of 50 ms. The polarity was linear and its direction coincided with one horizontal axis of the room. These noise components were set for the purpose of mimicking real MFs that leak out from various electronic apparatuses.

These waves were amplified and supplied to the exposure room by a power amplifier (Model 7572, Techron, IN) in the constant current mode. The intensities of all fields generated were confirmed using a three-axis flux gate sensor (MAG-03MC, Bartington Instruments).

2.3. Subjects

In Experiment 1, 30 healthy subjects (21 males and 9 females) aged 22–42, were selected. They were divided into two groups of 15 persons each so that the distributions of age and sex in the two groups were similar. One group was for exposure to MF with horizontal axis, and the other was for that with vertical axis.

In Experiment 2, 13 healthy subjects (seven males and six females) aged 22–25, participated in the study.

In Experiment 3, seven healthy men aged 20–37, participated in the study. Females were not included because the experiment had another aim of investigating whether MF exposure influences nighttime hormonal secretion, which is sometimes difficult to analyze in females because of their menstrual cycle. All subjects conducted their regular daily routines and had regular sleeping habits, and had no chronic disease or a recent acute illness. They were requested to go to sleep as regularly as possible during at least 1 week before the experiment.

All of the subjects were provided all information about the experiments and gave their written consent before the experiments were started. The design of the study was approved by the Human Rights Committee of the National Institute for Environmental Studies.

2.4. Experimental schedule

The protocols of the three experiments are schematized in Fig. 3.

2.4.1. Experiment 1

Each subject performed an 85-min protocol in a day. A 1-day protocol comprised five sessions, and each subject

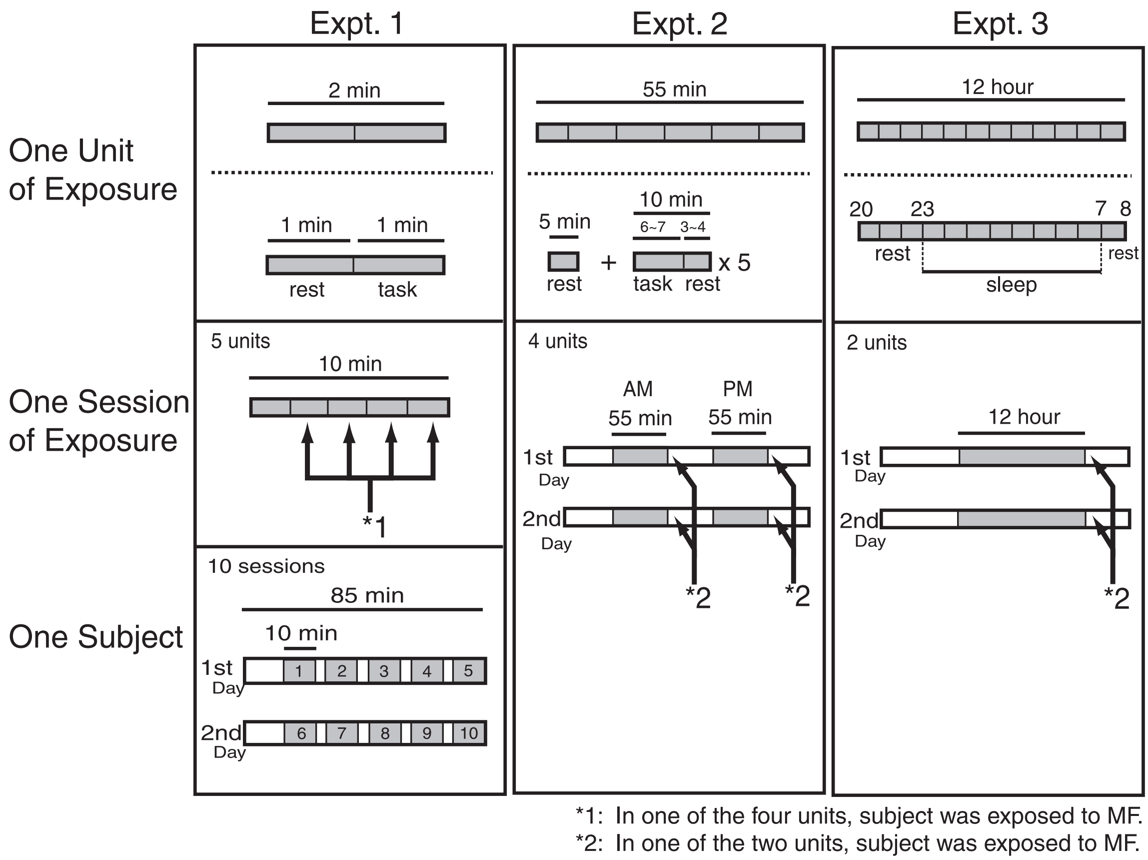

Fig. 3. Schema of the experimental schedule. Each session of exposure to one mode of field consisted of five, four, and two units in Experiments 1, 2 and 3, respectively. Each subject was exposed to 10 modes of MF in Experiment 1, and one mode of MF in Experiments 2 and 3.

underwent a total of 10 sessions in two separate days. The time of day for performing the protocol was determined for each subject in order to be identical in the 2 days and not to be within 2 h after a meal because HRV indices might change transiently after taking a meal (Kageyama et al., 1996). By the same reason, subjects were requested to take no food or drink within 2 h before the experiment.

Throughout the protocol in a day, the subjects were instructed to maintain a sitting position at the center of the exposure room under continuous recording of RRIs. The protocol was started with a 15-min relaxation followed by five sessions of 10-min each with 5-min breaks between sessions. During the breaks, the subject was allowed to read a book or take a rest on the chair but not to take a nap.

Each 10-min session consisted of five successive units of a pair of 1-min rest and 1-min task performance. During the task performance, the subject was given an addition task, in which the subject was requested to continuously add up neighboring two one-figure numbers in rows and writing the first digit of the sum on the paper for the Uchida-Kraepelin Psychodiagnostic test (Psychotechnological Institute, Japan). Since the aim of the task performance was to keep the subject constantly alert during the experiment without any mental strain, the subject was requested to perform the calculation at his own pace. The timing for the subject to change his mode from rest to task and vice versa was announced by a talking clock on the table. During the time for rest, the subject was allowed only to take a rest on the chair and was requested to be as motionless as possible (at least during the period between 5 s after beginning and 5 s before the end of the task). The subject was never requested to be conscious of his breathing rate throughout the experiment.

Before the experiment, the subject was told that he would be exposed to MF in one of the five units for 2 min, and indeed, MF was generated in a unit except the first one. In this way, data obtained immediately before exposure were never missed in any session. The MF mode was varied in each session, and thus the 10 modes described above were applied to each subject in random order.

2.4.2. Experiment 2

Each subject performed a 55-min protocol in one session. A 1-day protocol comprised two sessions, one of which was in the morning and the other in the afternoon, and the subject underwent a total of four sessions in two separate days. Throughout one session, the subject maintained a sitting position at the center of the exposure room under continuous recording of RRIs. The protocol started with a 5-min relaxation and was followed by five successive sessions of 10 min each, which consisted of 6 or 7 min of task performance and a 3- or 4-min break between sessions. During breaktime, the subject was allowed to take a rest on the chair but not to take a nap.

During the task, the subject had to take cognitive performance function tests by looking at a display and handling a keyboard.

2.4.3. Experiment 3

Each subject underwent three night sessions. The first night was for adaptation to the experimental conditions, in which the same equipment as that used in experiments at night was attached to the subject. The other two nights were for MF exposure and for control, and the order of the nights, which was unknown to the subject, was determined by the experimenter to avoid bias. The first and second nights were in succession, and there was a 1-month interval between the second and third nights.

Each subject visited the treatment room at 1900 h, and was inserted a 20-gauge needle for catheterization into a vein in the left forearm. Then, saline was infused at a rate of 30 ml/h. After these procedures, he took the prepared dinner and rested until 2000 h. The subject was requested to stay in the experimental room from 2000 to 0800 h, during which he was either exposed or not exposed to MF. Drip infusion was continued for the entire period for collecting blood at 1-h intervals for other laboratory tests. He was instructed to sleep from 2300 to 0700 h, and throughout the period his RRIs were continuously recorded.

2.5. Sampling and analyzing RRIs

Electrocardiogram was recorded using chest-lead electrodes and was digitally converted at sampling intervals of 1 ms, and finally successive RRIs were collected into an ambulatory data logger (ML-2000, Mini-Mitter, OR). From the time series of RRIs, several sections were selected for HR/HRV analyses as shown below.

In Experiment 1, the RRIs in a 2-min unit immediately before exposure were considered to be the best control matching those of the exposure period because in the units after exposure an MF effect might remain, and thus this matched pair of units was selected for analyses. Any of the 2-min units consisted of one pair of 1-min rest and 1-min task performance, and from two 1-min units, a stationary section of the RRIs in each 1-min unit, a section from 5 s after the beginning to 5 s before the end of a unit, was extracted. This process of extracting four 50-s sections from each 10-min session was repeated for the entire data, and as a result, 40 sections of RRIs were obtained from each subject.

In Experiment 2, RRI data obtained during the task performance were not used in the present analysis because the task might cause mental strain and might influence HRV. Thus, only the 1-min section immediately before the end of the 10-min session was chosen, and 20 sections in total were analyzed for each subject.

In Experiment 3, every 30-min section during sleep was selected as the analysis unit. Thus, for each subject, 16 sections were obtained in a one-night session and 32 sections were obtained in total.

For each set of the RRI section data, six indices were calculated: (1) aRR: average RRI (ms); (2) sdRR: standard deviation of RRI (ms); (3)–(5) power spectral components (ms^2) in the frequency range of 0.02–0.05 Hz (pVLF), 0.05–0.15 Hz (pLF), and 0.15–0.50 Hz (pHF); and (6) L/H: ratio of pLF to pHF. The power spectrum of RRI was obtained using the following two calculation processes: (1) interpolating the discrete series of RRI versus time into regularly sampled signals using the spline function, and (2) executing autoregressive spectral analysis with a fixed model order of 15. These processes were carried out using the self-designed MS-DOS program.

All the RRI indices were expressed in common logarithmic values for standardization in preparation for statistical analyses.

2.6. Statistical analyses

All of the analyses were performed using SPSS 8.0 software (SPSS, Chicago, IL). The six RRI indices were subjected to multivariate analysis of variance with repeated

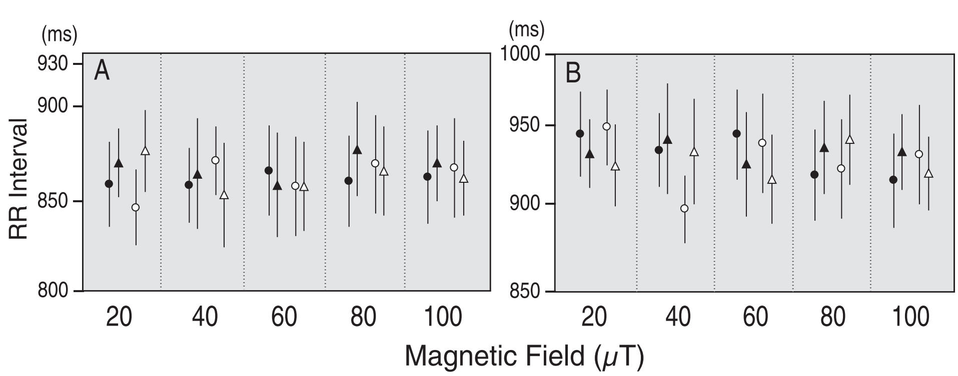

Fig. 4. Average RRIs obtained from subjects of group 1 (A) and group 2 (B) at rest in Experiment 1. Closed circles and triangles indicate data obtained before exposure, and open circles and triangles indicate data obtained during exposure. Circles indicate data for continuous exposure, and triangles indicate data for intermittent exposure. Each point is shown as a mean ± S.E.M. of logarithmic values in 15 subjects, and vertical axes are labeled using original values.

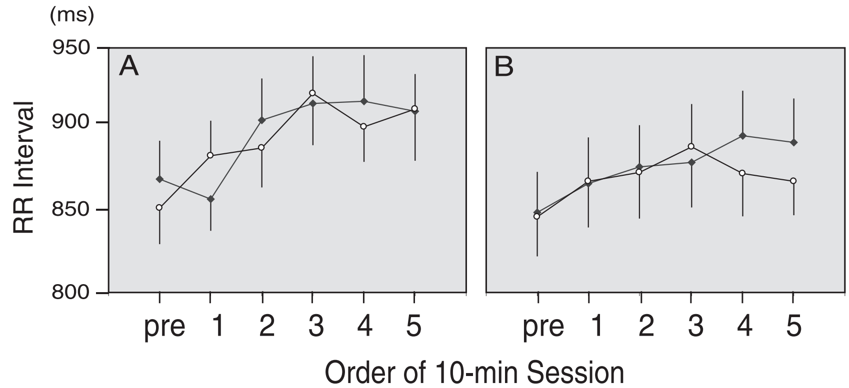

Fig. 5. Average RRIs obtained in 55-min sessions in the morning (A) and in the afternoon (B) in Experiment 2. Closed and open circles indicate data in control sessions and in exposed sessions, respectively. Each point is shown as a mean ± S.E.M. of logarithmic values in 13 subjects, and vertical axes are labeled using original values.

measures (rMANOVA). Hotelling's t^2 was selected as the statistics for MANOVA, and α was set at 0.05. Factors for the rMANOVA were as follows.

The RRI indices obtained in Experiment 1 had four within-subject factors and one between-subject factor. Exposure (control and exposed), intensity (20, 40, 60, 80, and 100 μT), continuity (continuous and intermittent), and status (rest and task) were the within-subject factors, and polarity (horizontal and vertical) was the between-subject factor. Because two levels of the status, rest and task, must be differentiated from each other neurophysiologically, analysis was carried out separately in each status.

The RRI indices in Experiment 2 had three within-subject factors, namely, order (first, second, third, fourth, and fifth of 10-min session), time (morning and afternoon), and exposure (control and exposed). Similarly, the RRI indices obtained in Experiment 3 had two within-subject factors: time (1st–16th of 30-min section) and exposure (control and exposed).

3. Results

Fifty subjects participated in the studies, and none of them declared any change of physical or mental condition when they were exposed to ELF-MFs. Furthermore, none of them knew when they were exposed to the fields, as determined from their answers to our questions after one unit of experiment was over. In conclusion, none of the subjects detected ELF-MFs supraliminally.

Figs. 4–6 show the extracted results of the profiles of six HR/HRV indices in the three experiments. The results of the

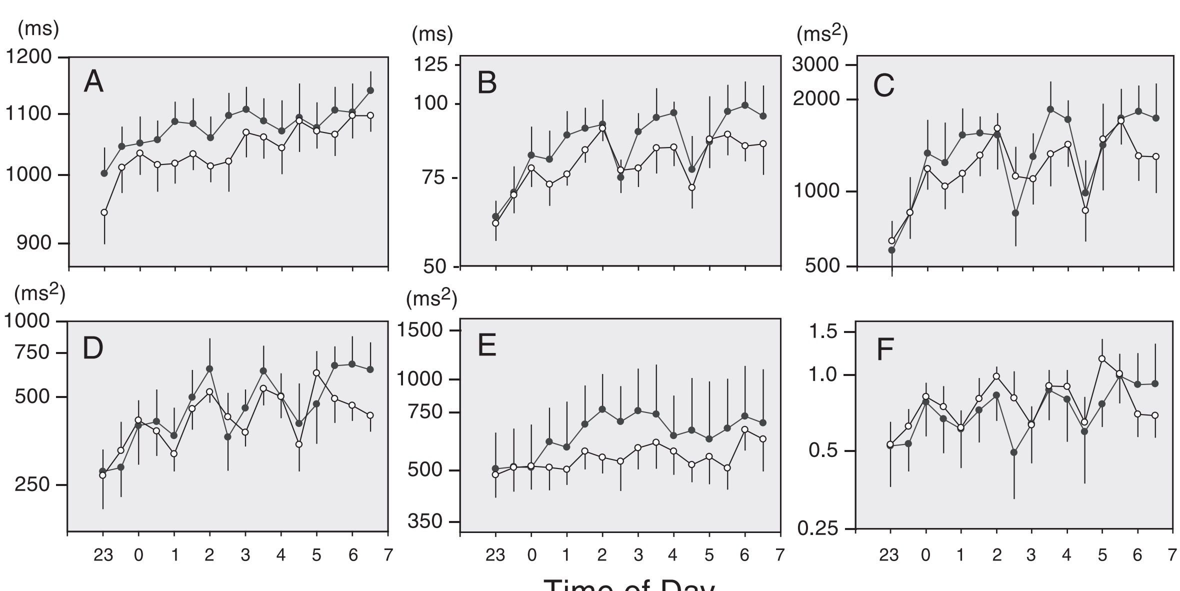

Fig. 6. HR/HRV indices: (A) aRR, (B) sdRR, (C) pVLF, (D) pLF, (E) pHF, and (F) L/H, obtained in Experiment 3. Closed and open circles indicate data for control nights and exposed nights, respectively. Each point is shown as a mean ± S.E.M. of logarithmic values in seven subjects, and vertical axes are labeled by original values.

Table 1
Results of repeated measures MANOVA

Experiment	Factor	Resting		Calculating	
		F (df)	P	F (df)	P
Experiment 1	Main effect				
	Exposure (preexposed and exposed)	1.29 (1,14)	0.30	0.70 (1,14)	0.63
	Intensity (20, 40, 60, 80, and 100 μT)	0.94 (4,56)	0.54	0.85 (4,56)	0.65
	Continuity (continuous and intermittent)	0.44 (1,14)	0.82	0.21 (1,14)	0.96
	Polarity (vertical and horizontal)				
	Interaction				
	Exposure × Intensity	0.88 (4,56)	0.62	0.67 (4,56)	0.85
	Exposure × Continuity	0.95 (1,14)	0.47	0.82 (1,14)	0.55
	Exposure × Polarity	0.35 (1,14)	0.88	1.09 (1,14)	0.39
	Exposure × Intensity × Continuity	1.05 (4,56)	0.40	1.06 (4,56)	0.39
	Exposure × Intensity × Polarity	0.66 (4,56)	0.87	0.47 (4,56)	0.98
	Exposure × Continuity × Polarity	1.17 (1,14)	0.35	1.84 (1,14)	0.14
	Exposure × Intensity × Continuity × Polarity	1.47 (4,56)	0.088	0.77 (4,56)	0.75
Experiment 2	Main effect				
	Exposure (nonexposed and exposed)	1.34 (1,12)	0.35		
	Time (AM and PM)	1.23 (1,12)	0.39		
	Order (1, 2, 3, 4, 5)	2.95 (4,48)	0.0000		
	Interaction				
	Exposure × Time	0.41 (1,12)	0.83		
	Exposure × Order	0.73 (4,48)	0.83		
	Exposure × Time × Order	1.52 (4,48)	0.059		
Experiment 3	Main effect				
	Exposure (nonexposed and exposed)	0.39 (1,6)	0.83		
	Time (1st–16th of 30-min sections)	3.13 (15,90)	0.0000		
	Interaction				
	Exposure × Time	1.15 (15,90)	0.20		

rMANOVA test using all the data are summarized in Table 1. In any of the three experiments, the analyses revealed no significant main effect of exposure and no significant exposure-related interaction.

4. Discussion

In the present study, human volunteers were exposed to ELF-MFs that have similar characteristics to those of fields to which humans are exposed in their daily lives. As a result, the observations did not support the hypothesis that exposure to ELF-EMF may cause an alteration of either HR or any component of the HRV power spectrum.

In Experiment 1, the subjects were carefully set under conditions in which their physical and mental states were stable, and a pair of 2-min data obtained both immediately before and during the exposure was collected from each session. Consequently, the statistical test demonstrated that short-term exposure to MF does not alter HR/HRV acutely, and this finding suggests the absence of a direct action of MFs on ANS.

In Experiments 2 and 3, the subjects were exposed to ELF-MF for longer periods than in Experiment 1, and the results showed no influence. Both protocols of Experiments 2 and 3 were similar to those of experiments conducted by the group in the Midwest Research Institute (MRI). The MRI group performed two series of experiments. Their first experiment and our Experiment 2 were conducted to examine whether MF exposure for periods ranging from 1 to 6 h influenced cognitive performance tests or RRIs, and their second experiment and our Experiment 3 were conducted to study the effect of MF exposure during sleeping at night.

In the first experiment by the MRI group, subjects were exposed to 60 Hz EF and 60 Hz MF simultaneously at three intensity levels for 3–6 h, and they found a significant decrease in HR when the subjects were exposed to EF (9 kV/m) + MF (20 μT), and no change when exposed to weaker (6 kV/m + 10 μT) or stronger (12 kV/m + 30 μT) fields (Cook et al., 1992; Graham et al., 1994). Although the detected effects showed some properties difficult to be understood physiologically, namely, a nonlinear dose–response relationship and dependence on the order of the two sessions (exposure and control sessions), taking these together with our results of Experiment 2 (exposure to 50 Hz/20 μT MF for 55 min) raises the following two possibilities: (1) EF, but not MF may influence HR/HRV, and (2) the effect of EMF may emerge more than 1 h after exposure. The former seems unlikely because there is, at present, a united view that the possible biological effect of ELF-EMF is attributable not to alternating EF but to alternating MF, which induces an eddy current in living bodies (Working Group for EMF-RAPID Program, 1998; NIEHS, 1999). The latter suggests an indirect action of MF on cardiac dynamics, such as inducing hypnosis, reducing body temperature, and shifting the phase of the intrinsic circadian clock. Such possibilities would be examined in an experiment of exposure for periods longer than a few hours, and both the second experiment of the MRI group and our Experiment 3 correspond to such an experiment.

The second experiment of the MRI was further divided into two series, one of which was linked to the study of profiles of nighttime blood hormones, particularly melatonin, and the other was conducted similarly to the former but without collection of blood. In the former session, nighttime exposure to 60 Hz/28.4 μT MF in young men resulted in a decrease in the LF power of HRV (Sastre et al., 1998), but in the latter session, no change was observed in either young men exposed to 60 Hz/28.4 and 128.4 μT MF or middle-aged women exposed to 60 Hz/28.4 μT MF, while both middle-aged men exposed to 60 Hz/28.4 μT MF and young men exposed to 16 Hz/28.4 μT MF showed a decrease in LF power (Graham et al., 2000a,b; Sastre et al., 2000). All the results except that for exposure to 16 Hz MF showed the common trend of the absence of any change in HR. To summarize their results, the detection of MF effects depended on the frequency of applied fields and the features of subjects such as age and gender.

They attributed the discrepancy in their results of the two sessions in young men to the difference in the sleeping status, because sleep might be influenced when subjects were subjected to blood sampling in the first session, which was not the case in the second (Graham et al., 2000a). In the present study, we were successful in collecting blood without disturbing the subjects' sleep as determined from the results of polysomnography that was simultaneously executed. Based on the results of these studies by two independent laboratories, we may assume that the MF effect is likely to be undetectable in sleeping subjects because sleep numbs the sensitivity to the fields. The discrepancy between the results of younger and middle-aged men may suggest the existence of an age-dependent effect of the fields. Although we did not examine middle-aged subjects in Experiment 3, we think that such an effect is questionable because the result of the MRI group that showed higher sensitivity to the fields in middle-aged men than in their younger counterparts does not agree with the general observation that older subjects have lower ANS activity than younger subjects (Odemuyiwa, 1995; Kageyama et al., 1997).

Our results of Experiment 3 demonstrated that exposure to ELF-MFs during nighttime sleep does not influence HR/HRV. This was supported by the results that indicated the absence of MF action of shifting the circadian clock: both the second experiment of the MRI group and our Experiment 3 investigated blood melatonin levels and neither study found any effect of MF exposure (Graham et al., 1996; Kurokawa et al., 2003).

To our knowledge, three other experiments using an experimental room with a precise apparatus for ELF-MF exposure were reported. Whittington et al. (1996) performed an experiment in which volunteers were exposed to 100 μT MFs for 9 min by a head coil system, and found no effect of the fields on HR. Sait et al. (1999) carried out an experiment similar to ours, and observed that continuous exposure to circularly polarized 50 Hz/28 μT MFs for 100 or 150 s resulted in the reduction of HR and LF power of HRV. Furthermore, Griefahn et al. (2001) applied 16.7 Hz MFs that are generally emitted by electrified railways in several countries, and the results of nighttime exposure indicated no effect of the fields on HR. Although the results of the second research by Sait et al. (1999) do not agree with our results of Experiment 1, they seem to provide weak evidence of the MF effect because the researchers performed statistical analysis by multiple comparison by repeating the Student's *t*-test using data from many trials of exposure consisting of altered continuity (continuous and intermittent), waveform of the fields (sinusoidal and square), and order of session (OFF → ON and ON → OFF).

To summarize the relationship between exposure to ELF-EMF and HR/HRV that has been reported so far, the detected effects of the fields seem to be very variable depending on many factors such as various characteristics of fields, design of experiments, and features of subjects. In the present study, three series of exposure to ELF-MFs at different periods did not influence HR/HRV in human volunteers, which indicates a small probability of an MF effect. Recent investigations have shown that HR/HRV may be a useful indicator for predicting the prognosis of acute myocardial infarction (Kleiger et al., 1987; Bigger et al., 1992). An epidemiological study has suggested that occupational exposure to ELF-MF may be related to increased risk of death from arrhythmia-related conditions and myocardial infarction (Savitz et al., 1999). These findings seem to emphasize the importance of clarifying the relationship between exposure to ELF-EMF and HR/HRV. Our results support the notion of absence of relationship between them.

Acknowledgements

This study was supported by a grant from the National Institute for Environmental Studies in Japan (grant number: T-13). We specially thank Dr. Plamen Doynov and Dr. Charles Graham (Midwest Research Institute) for cooperation in the construction of the experimental room. We also thank Dr. H. Hayashi (University of Gunma) for assistance in statistical analysis, and Dr. Miyuki Sadamatsu and Dr. Shun-ichi Furukawa (University of Tokyo) for help in nighttime experiments.

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