Cardiac Autonomic Control Mechanisms in Power-Frequency Magnetic Fields: A Multistudy Analysis

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Heart rate variability (HRV), a noninvasive indicator of autonomic control of cardiac activity, is predictive of long-term cardiac morbidity and mortality. Epidemiologic research suggests that occupational exposure to power-frequency magnetic fields may be associated with autonomically mediated cardiac mortality. Results from our laboratory studies of humans exposed to 60-Hz magnetic fields overnight, however, are inconsistent. HRV is altered in some studies but not others. To clarify this, the pooled data from seven studies involving 172 men were analyzed to test specific hypotheses concerning this inconsistency. After analysis, we excluded *a*) measurement drift or instability over time because HRV was stable under sham-exposed conditions across all studies; *b*) inadequate statistical power or failure to maintain double-blind controls; *c*) differences in field intensity (28.3 vs. 127.3 μT) or exposure pattern (intermittent versus continuous) as main effects; or *d*) the inclusion of individuals sensitive to magnetic field exposure in some studies but not others. Four separate analytic techniques failed to identify a valid subpopulation of sensitive individuals. In some studies, however, hourly blood samples were collected using an indwelling venous catheter. HRV alterations occurred during intermittent exposure in these studies ($p < 0.05$) but not in similar studies without blood sampling. This result suggests a field interaction with modest arousal or disturbance. Because HRV is tightly coupled to electroencephalographic activity during sleep, these results are physiologically plausible and suggest that HRV alterations during exposure to magnetic fields may occur when accompanied by increases in physiologic arousal, stress, or sleep disturbance. *Key words*: **EEG, EMF, heart rate variability, human, sleep, stress.** *Environ Health Perspect* **108:737–742 (2000). [Online 28 June 2000]**
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Heart rate variability (HRV) is mediated by the interplay of the sympathetic and parasympathetic branches of the autonomic nervous system (ANS). Quantitative assessment of the HRV frequency spectrum derived from the electrocardiogram (ECG) provides a reliable, noninvasive method to assess autonomic control of cardiac activity (*1,2*). HRV is of particular interest because of its value in predicting long-term cardiac morbidity and mortality. Reductions in specific components of the HRV frequency spectrum are prognostic for the development of heart disease in large prospective cohort studies (*3–6*) and in studies of coronary artery disease, postinfarction risk, and sudden cardiac death (*7–9*).

Sastre et al. (*10*) recently described three studies performed in our laboratory in which 77 healthy young men were exposed during night sleep to circularly-polarized 60-Hz magnetic fields at resultant intensities of 1.4 or 28.3 μT (14 or 283 mG, respectively). The objective of these studies was to evaluate the effects of exposure on the pineal hormone melatonin measured in hourly blood samples; however, because of our interest in possible exposure effects on cardiac function, we also recorded cardiac interbeat intervals continuously throughout the test nights to analyze HRV. Intermittent exposure at 28.3 μT, an intensity in the occupational exposure range, resulted in statistically significant alterations in HRV, replicable over two independent double-blind studies. Specifically, exposure reduced power in the low-frequency (LF) band (0.0–0.10 Hz) of the HRV spectrum and increased power in the high-frequency (HF) band (0.15–0.40 Hz). LF power alterations reflect the actions of thermoregulatory and blood pressure control mechanisms on the heart, primarily mediated through the sympathetic branch of the ANS. HF power alterations reflect respiratory control mechanisms and consequent sinus arrhythmia, mediated through the parasympathetic branch of the ANS. These effects did not occur in the third study when field exposure was continuous, nor did they occur when volunteers were exposed to the lower intensity magnetic field.

The potential environmental health implications of these results were recently highlighted by Savitz et al. (*11*). Mortality from cardiovascular disease in relation to occupational magnetic field exposure was examined in a cohort of approximately 140,000 male electric utility workers employed in the United States between 1950 and 1988. After adjusting for age, race, social class, year, and active work status, mortality from arrhythmia-related disease and acute myocardial infarction was associated with longer duration in jobs with elevated exposure. Mortality due to atherosclerosis and chronic coronary heart disease was not associated with these exposure indices. The former two disease categories are linked to altered autonomic cardiac control, whereas the latter two categories are not (*4,5,12*).

It was important to learn more about the specific test conditions under which changes in HRV occur. Thus, we collected HRV in four human laboratory exposure studies. Across these studies, HRV was assessed during intermittent and continuous exposure conditions, at different field intensities, and under conditions in which hourly blood samples were not collected. Unlike the previous studies, field exposure had little or no effect on HRV. To better understand why effects on HRV have been found in some studies and not others, data from all studies were combined to create an integrated database containing relevant HRV information on 172 volunteers. This made it possible to test hypotheses that could not adequately be addressed in any single study alone and also to perform comparative analyses to identify possible confounders or predictor variables. Here we describe the results of our analyses and discuss their implications.

Materials and Methods

Common characteristics. Table 1 lists the general characteristics of the seven studies included in the multistudy database. For ease of presentation, the studies are broadly grouped by type of experimental design. Studies A, B, and C used an independent-groups design (i.e., each subject was assigned to a single test or control condition, and statistical analysis evaluated differences between groups). The remaining four studies used the more powerful (*13*) repeated-measures design (i.e., all subjects participated in all test and control conditions in counter-balanced order, and statistical analysis compared the effects of the different conditions

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Table 1. Characteristics of studies included in the integrated database.

Study characteristics	Study identification						
	A	B	C	D	E	F	G
Study design							
Double-blind test protocol	✓	✓	✓	✓	✓	✓	✓
No-exposure control condition	✓	✓	✓	✓	✓	✓	✓
Random subject assignment	✓	✓	✓	✓	✓	✓	✓
Alpha set at $p \leq 0.05$	✓	✓	✓	✓	✓	✓	✓
Independent-groups design	✓	✓	✓	–	–	–	–
Repeated-measures design	–	–	–	✓	✓	✓	✓
Counter-balanced testing	–	–	–	✓	✓	✓	✓
Subject characteristics:							
Number of subjects ($n = 172$)	27	18	30	23	26	24	24
Age range (18–35 years)	✓	✓	✓	✓	✓	✓	✓
Sex (male)	✓	✓	✓	✓	✓	✓	✓
Test conditions							
Number of sessions per subject	1	1	4	2	2	3	3
Duration (2300–0700 hr)	✓	✓	✓	✓	✓	✓	✓
Frequency (60 Hz)	✓	✓	✓	✓	✓	✓	✓
Field polarization (circular)	✓	✓	✓	✓	✓	✓	✓
Blood sample collected hourly	✓	✓	–	✓	✓	–	–
Sham exposure (< 0.02 μT)	✓	✓	✓	✓	✓	✓	✓
Continuous exposure (μT)	–	–	–	–	28.3	28.3	127.3
Intermittent exposure (μT)	28.3[a]	28.3	28.3	28.3	–	28.3	127.3
Measures							
ECG	✓	✓	✓	✓	✓	✓	✓
HRV/heart rate	✓	✓	✓	✓	✓	✓	✓

[a]This study also evaluated intermittent exposure effects at 1.4 μT.

within each individual). We randomly assigned subjects to conditions or testing orders in all studies, and we followed double-blind procedures to prevent the subjects as well as the investigators from knowing when a no-exposure control or field exposure test condition was in effect in any given session. Cohen et al. (*14*) and Doynov et al. (*15*) describe the double-blind control system and its successful use in previous research.

HRV data were available for 172 subjects who participated in the seven studies. These subjects were healthy young men between 18 and 35 years of age who had normal sinus rhythm, regular sleep and dietary habits, and were not taking medications. The study protocols were approved by the Midwest Research Institute (MRI) Institutional Review Board for Human Studies (Kansas City, MO), and we obtained written informed consent from each volunteer before participation.

Exposure facility. The three studies described in Sastre et al. (*10*) are identified as studies A, D, and E in Table 1. These studies were performed in the original exposure facility at the MRI. Characteristics of this facility have been documented by the U.S. Department of Energy (*16*), and the facility is described by Cohen et al. (*14*). The four subsequent studies were performed in the new exposure facility constructed at the MRI. Characteristics of this facility have also been documented as part of the U.S. national Electric and Magnetic Field Research and Public Information Dissemination Program directed by the National Institute of Environmental Health Sciences (*17*). The facility is described in Doynov et al. (*15*). Basic exposure characteristics (e.g., field uniformity, phase angle, and harmonic content) of the 60-Hz alternating-current magnetic field generated in the original and in the new facility are in close agreement.

In each study conducted in the new facility, the subject slept on a bed in a sound-attenuated and air-conditioned exposure test room (a cube approximately 2.4 m on each side). Magnetic field generation at the selected frequency, intensity, waveform, pattern, and duration was controlled by software operating in conjunction with power generation systems. To produce the circularly polarized field, one axis of the field was phase-shifted 90° with respect to the other axis. The Merritt-type concentric coil systems were located out of the subject's sight behind the walls, ceiling, and floor of the exposure room [Doynov et al. (*15*) provides additional details]. The subject slept with a north–south body orientation. The horizontal axis of the field was oriented north–south and the vertical axis was perpendicular to the floor. In six of the seven studies in Table 1, subjects were exposed to a uniform (± 2.5%) sinusoidal 60-Hz magnetic field at a resultant flux density of 28.3 μT. Study G evaluated exposure effects to the same field but at a higher resultant intensity (127.3 μT). This intensity is relevant to the upper range of occupational exposures and to recommendations of the International Commission on Non-Ionizing Radiation Protection limiting exposure in the general population to 100 μT at 50 Hz (*18*). All studies included a no-exposure sham control condition in which the magnetic field generation coils were not energized and the subjects were exposed only to the ambient background 60 Hz magnetic field measured in the laboratory [≤ 0.2 μT (2 mG)]. This intensity is relevant to typical residential exposures.

As shown in Table 1, subjects were exposed overnight to an intermittent magnetic field in all but one study (E). The pattern of intermittent exposure used in these studies followed the protocol described in Sastre et al. (*10*), and consisted of alternating 1-hr field-on and field-off periods. During field-off hours, the field generation coils were not energized. During field-on hours, the field cycled on and off at 15-sec intervals. A zero-current crossing technique allowed the magnetic fields to be switched without introducing artifacts because of the generation of HF magnetic field transients at the switch points. In study E the volunteers were exposed only to the continuous magnetic field, and in studies F and G they were exposed to both intermittent and continuous magnetic fields. The decision to emphasize intermittent field exposure and to use circularly polarized fields was based on previous research indicating that such exposure is associated with alterations in human physiology (*10,19,20*) and also on rodent research reporting that circularly polarized fields are more effective than linearly polarized fields in reducing nocturnal concentrations of the pineal hormone melatonin (*21*).

Procedures. All studies were performed at night. Subjects were instructed to refrain from consuming alcohol for 24 hr before a test session and to have no caffeine after 1700 hr on the day of a session. On arrival at the laboratory, subjects changed into sleepwear, vital signs were recorded, and the ECG recording sensors were attached. The lights in the exposure test room were turned off at 2300 hr, the field or sham exposure condition was activated, and the subject remained in bed until 0700 hr. Subjects were monitored through the night via closed-circuit TV, open audio intercom, and the physiologic recording system. Four studies (Table 1) involved the collection of hourly blood samples through the night for melatonin analysis. In these studies, an indwelling butterfly catheter was inserted into a vein in the arm or hand at the start of a test session to minimize disturbance to the subject during subsequent sample collections. The study nurse entered the test room each hour on the hour to collect the samples. In the repeated-measures studies, order of field exposure and sham control sessions was counter-balanced such that equal numbers of subjects participated in each condition on each night.

Measures. Recording sensors were attached to skin sites on the right clavicle and the seventh intercostal space under the left axillary midline, corresponding to the standard ECG lead II configuration. In the three studies reported by Sastre et al. (*10*), the lead II ECG was passed in real time through a modified Schmitt trigger hardware detector. The output of the trigger, which is a pulse at the time of the R wave, was continuously recorded to produce the series of cardiac interbeat intervals needed to derive HRV. In subsequent studies, the full lead II ECG was digitally recorded through the night. Custom software that permitted expert operator review was then used to identify the R waves and generate the interbeat interval series data. Physiologic recording was accomplished using a Beckman multichannel recorder (type R612) in the earlier studies, and a model 15 Neurodata physiological data acquisition system (Astro-Med, Inc., West Warwick, RI) in the subsequent studies. Both systems used optically isolated amplifiers with high common mode rejection, high input impedances, and isolated power supplies.

For quantitative analysis of HRV, the interbeat interval data were first converted to instantaneous heart rate to provide a regularly spaced time series with a 1-sec resolution. The time period selected for analysis was midnight to 0600 hr. Each hour was divided into three equal periods containing 1,024 points. After detrending and applying a Hamming window, a digital Fourier transform was performed on each period. Results were expressed as the power spectrum in the 0.0–0.5 Hz range. In the three previous studies (Table 1; studies A, D, and E) described in Sastre et al. (*10*), the cardiac data collected in the 5-min intervals immediately before and after the hourly blood collections were excluded from analysis to eliminate possible artifacts associated with this procedure. HRV analysis in these studies was based on data collected in the six 50-min intervals from midnight to 0600 hr, each divided into three equal time segments containing 1,024 points. In the subsequent studies, HRV analyses were based on data collected over the entire hour. In the analysis of study F (Table 1), we examined whether the results obtained with 50-min intervals differed substantially from the results of analyses that used the full hours; no significant differences were observed, so full hours were used in all subsequent studies.

We used analysis of variance (ANOVA) as the primary statistical technique to test for differences between exposure and control conditions. ANOVA was performed for total power in all frequency bands of the HRV spectrum (0.0–0.50 Hz) and for absolute and percent power in the LF (0.0–0.10 Hz) and HF (0.15–0.40 Hz) bands. The major analysis variables evaluated were study (the seven studies in Table 1), hour (the 6 hr from midnight to 0600 hr), and period (the three time intervals containing 1,024 data points in each hour). Results were considered statistically significant if $p \leq 0.05$. In the repeated-measures studies, probability values were corrected for lack of sphericity using the Huynh-Feldt epsilon technique. Significant main effects or interactions were followed up with simple effects analyses.

Results

The biologic magnitude of the reduction in HRV observed by Sastre et al. (*10*) was approximately 17%. Power analysis determined that the subsequent studies possessed sufficient statistical power to detect a similar degree of HRV suppression. Analyses were performed to test four hypotheses.

Hypothesis 1: the observed lack of replication is due to drift or instability over time in the HRV measures collected for comparison purposes in the no-exposure sham-control sessions. In each of the seven studies in Table 1, a field-related effect was defined as a statistically significant difference between the HRV measures collected during the exposure sessions and the HRV measures collected during the no-exposure control sessions. Thus, the lack of replication could be due to alterations over time in the HRV values used for comparison purposes. HRV data from the initial no-exposure control session in each study were available for 131 subjects (this included the 34 men assigned to the no-exposure control groups in the independent-group studies A, B, and C). We performed ANOVA to test for differences between studies. The between-subjects variable was study and the within-subject variables were hour and period. HRV measures collected in the no-exposure control conditions did not differ between studies [LF: $F(6,124) = 0.57$, $p = 0.75$; HF: $F(6,124) = 0.33$, $p = 0.92$]. Hypothesis 1 was not supported.

Hypothesis 2: the hourly blood collection procedure is a critical variable in determining HRV responsiveness to magnetic field exposure. Alterations in HRV are closely coupled to several stages of sleep in humans. If subjects were awakened or aroused by the hourly blood sampling procedures used in some studies, this could affect the time course and pattern of HRV changes observed over the night. Data were available from five studies, all involving intermittent exposure to the magnetic field at an intensity of 28.3 μT. Three of these studies included hourly blood collections and two did not. We performed separate analyses to compare studies with independent-group designs and studies with repeated-measures designs. For studies with independent-group designs (A, B, and C), data were available for 66 subjects. The between-subjects variables were blood sampling (yes or no) and field (exposed or control) and the within-subject variables were hour and period. ANOVA did not reveal any statistically significant main effects or interaction effects involving blood sampling and field or hour, indicating that the blood collection procedure was not a significant factor in determining the pattern of HRV responsiveness observed over the night in the independent-groups studies. This conclusion, however, is limited by the fact that only 8 of the 24 exposed subjects included in this analysis were drawn from study A, in which significant field-related effects on HRV were found.

For the repeated-measures studies (D and F), data were available for 47 subjects. The between-subjects variable was blood sampling and the within-subjects variables were field, hour, and period. ANOVA revealed that the blood collection procedure was a significant factor in determining HRV responsiveness during magnetic field exposure in these studies in which each subject served as his own control. Figure 1 plots hourly mean values across the night for percent power in the LF and HF bands under magnetic field exposure conditions. Figure 1 contrasts the differences observed in HRV when subjects are exposed to the magnetic field with and without the concomitant presence of hourly blood collections. Figure 1A shows that percent LF power does not differ in the initial 20 min of exposure (mean = 49%) under blood collection and no-blood-collection conditions. It then becomes progressively differentiated with increasing exposure duration as a function of the presence or absence of blood collection. When blood was not collected, LF power increased through the night; when blood was collected LF power was suppressed, remaining essentially unchanged across the night [$F(5,225) = 2.29$, $p = 0.05$]. Figure 1B illustrates that percent HF power also becomes progressively differentiated over the exposure night as a function of the presence or absence of blood collection. Percent HF power increased during field exposure when blood was collected and was generally lower during field exposure when blood was not collected [$F(5,225) = 2.43$, $p = 0.04$]. In contrast, analysis of the HRV data obtained in the no-exposure sham-control sessions failed to reveal similar differential effects on LF and HF percent power as a function of blood collection. These results essentially replicate the earlier findings of Sastre et al. (*10*), and they provide support for hypothesis 2.

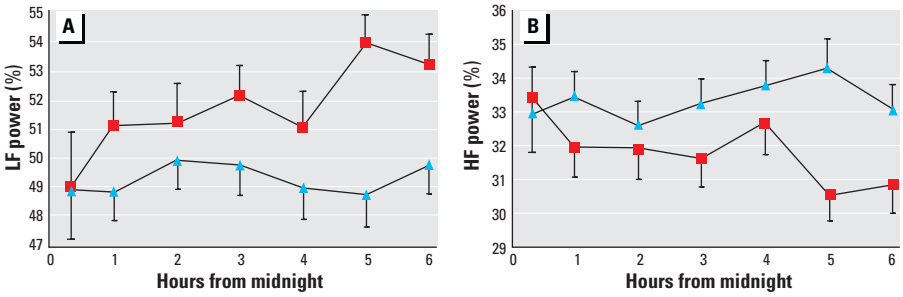

Figure 1. HRV differences in 47 healthy young men during intermittent magnetic field exposure (60 Hz, 28.3 μT), with (triangle) and without (square) the concomitant collection of hourly blood samples. Plots show hourly mean (± SD) values for percent power in (*A*) LF (0.0–0.10 Hz) and (*B*) HF (0.15–0.40 Hz) HRV spectral bands; field-activation hours were 0–1, 2–3, and 4–5 hr after midnight. LF power was suppressed ($p < 0.05$) and HF power was enhanced ($p < 0.04$) during magnetic field exposure only when primed by the blood collection procedures.

Because the blood collections occurred on the hour, we would also expect physiologic arousal to be most evident in the first third of the hour. Further analysis indicated this was the case. Blood collection × hour × period interactions were found for both percent LF power [$F(10,450) = 1.89$, $p = 0.05$] and percent HF power [$F(10,450) = 2.01$, $p = 0.03$]. When blood samples were collected, LF power was lower in the first third of the hour and HF power was higher in the first third; when blood samples were not collected no such patterns were observed. These differential patterns in LF and HF power were evident after the first hour of exposure.

Hypothesis 3: alterations in HRV are most evident during intermittent exposure to higher intensity magnetic fields. HRV data were collected under intermittent and continuous exposure conditions and at two magnetic field intensities (28.3 and 127.3 μT). For comparisons between intermittent and continuous exposure, we performed ANOVA on HRV data from two repeated-measures studies (D and E) in which 49 men were exposed at the same field intensity (28.3 μT). No statistically significant field-related differences in HRV measures were found as a function of intermittent versus continuous exposure. ANOVA across field intensities was performed using data from two repeated-measures studies (F and G). Data were available for 24 subjects exposed to an intermittent magnetic field of 28.3 μT and for an additional 24 subjects exposed under identical testing conditions to the same field at an intensity of 127.3 μT. No statistically significant differences in HRV measures were found as a function of field intensity. Hypothesis 3 was not supported.

Hypothesis 4: the lack of replication in HRV results across studies is due to the inclusion of individuals who are sensitive to magnetic field exposure in some studies but not in others. There is little evidence for human perception of, or sensitivity to, power frequency magnetic fields until field intensities far above those described here are encountered (*22*). In each of the studies in Table 1, the volunteers could not judge whether they were in the field exposure or the control condition at better than chance levels. Nevertheless, there are reports of individuals with heightened sensitivity to electromagnetic fields, and attempts to account for such sensitivity have included reference to possible alterations in autonomic nervous system activity (*23*). Thus we attempted to develop objective physiologic criteria for the identification of possible magnetic-field-sensitive individuals based on the HRV measures collected in the present studies. Four separate approaches were explored using data from the 71 subjects who participated in the three intermittent-exposure repeated-measures studies in Table 1 (D, F, and G).

The pattern of changes observed in HRV over the night tends to be fairly consistent when measured within an individual. In our initial approach we reasoned that field-sensitive individuals would not display consistent HRV patterns between exposed and unexposed nights. To help identify such individuals, we computed a cross-correlation function (CCF) between control and exposed nights for each individual. Computation of the CCF was based on the values for total power and for absolute and percent power in the LF and HF spectral bands obtained in each of the sequential 20-min data collection periods throughout the night. The CCF was computed for a zero time lag and also for time lags of ± one, two, and three 20-min periods. This allowed us to identify correlations between control and exposed nights that might be perfectly synchronized in time (zero lag), up to correlations that might be displaced in time by ± 1 hr (lag 3). High values of the CCF would be indicative of consistent HRV patterns within an individual who is not sensitive, and small or negative CCF values between control and exposed nights could indicate a breakdown in consistency induced by the field. We defined individuals with two of the following three criteria as sensitive: small zero lag correlation, small positive maximal value of the CCF, and/or large absolute value of the most negative value of the CCF. Approximately 25% of the subject sample was defined as potentially sensitive according to this definition. If this approach were valid, we would expect only the sensitive subjects to exhibit the change patterns for LF and HF power shown in Figure 1. However, ANOVA did not identify different patterns of HRV in sensitive versus nonsensitive individuals at any of the lags evaluated.

In Sastre et al. (*10*) power in the LF band did not increase in the exposed subjects and it displayed a distinctly observable pattern over the night. In our second approach, we reasoned that any subject who exhibited LF power change patterns similar to those seen by Sastre et al. (*10*) could be tentatively labeled sensitive; the remaining subjects were labeled nonsensitive. Two scorers blinded to the exposure conditions evaluated all 71 subjects, using visual pattern recognition to identify the patterns of interest in all-night plots of the hourly mean values for LF power. Approximately 25% of the subjects were defined as potentially sensitive using this approach. We then attempted to predict this group difference derived from visual pattern recognition using a set of variables selected from other available data collected in the studies. The variables included mean heart rate, systolic and diastolic blood pressure before the first test session, age, order of exposure (control/exposed versus exposed/control), body mass index, Pearson correlation between LF power on control and exposed nights, and the standard deviation of heart rate on the control night. We performed stepwise logistic regression (SLR) on this set of variables to determine if any of them predicted group differences. The Pearson correlation between control and exposed nights was the single variable to enter the regression; it had marginal significance and explained a negligible amount (4%) of the variance.

In the Sastre et al. (*10*) studies, the magnitude of the field effect on HRV appeared to be greater earlier rather than later in the night. Thus, our third approach focused on the HRV data collected in the first 2 hr of exposure. We examined both the pattern and magnitude of LF power changes to see if they differentiated potential sensitive and nonsensitive subjects. Individual records were first evaluated by visual pattern recognition as previously described. Approximately 23% of the subjects were defined as potentially sensitive using this approach. We performed SLR on the set of variables described above to determine if any of them

predicted differences between groups. The Pearson correlation between control and exposed nights entered the regression analysis. It was of marginal significance and explained a negligible amount (5%) of the variance.

In our final approach, we developed two composite measures for HRV similar to the concept of area under the curve. We summed the values for LF power and also for total power over all 20-min periods of the night and calculated the value of the absolute difference between the composites for the control and exposed nights. This approach ignored the pattern of change in HRV observed over the night and reduced the difference between control and exposed sessions for an individual to a single index number. A low index value would indicate consistency across control and exposed sessions, whereas a high value could indicate enhanced sensitivity to the field. We then performed multiple regression against the set of variables listed above to see if the value of the index could be predicted by any of the variables in the selected set. The standard deviation of heart rate on the control night and systolic blood pressure before the first session entered the regression for LF power. Together these variables accounted for 16% of the variance. Only the standard deviation of heart rate on the control night entered the regression for total power, accounting for 12% of the variance.

None of the analysis approaches succeeded in identifying the subpopulation of interest in this group of healthy young men. Individuals sensitive to magnetic field exposure could not be readily identified or easily differentiated from "nonsensitive" individuals by correlational (CCF) techniques, by expert judgments based on visual pattern recognition, or by examination of the absolute differences in HRV parameter values in control versus exposure sessions. Hypothesis 4 was not supported.

Discussion

The results of our study have provided new information that could not be adequately obtained through analysis of any one study alone. The fact that no differences were found in the sham exposure control sessions across studies is important. This indicates that the observed lack of replication is not a function of instability over time under no-exposure control conditions, and that the biologic measure (HRV) selected for study is a stable and reliable marker in unexposed individuals.

Perhaps the most informative findings are the effects of including the hourly blood collections in the intermittent exposure studies using the more powerful repeated-measures experimental design. Blood sampling was a significant factor in determining HRV responses to field exposure over the night in these studies, and the results obtained essentially replicate the positive findings reported in Sastre et al. (*10*). It is also noteworthy that there was an interaction effect between the presence of blood collections, the hour of the night, and the period within the hour for both percent LF and HF power. When blood was collected, percent LF power was lower in the first third of the hour and percent HF power was higher in the first third; when no blood was collected, no such patterns were observed.

This pattern makes sense if the blood collection procedure directly increased the individual's state of physiologic arousal, with consequent changes in the HRV response to magnetic field exposure. It would be anticipated that such perturbations would be most evident in the first third of the hour (during and immediately after the collection of blood) and that they may be short-lived, as evident by a failure to see interactions during the later periods in the hour. Human HRV and sleep state are tightly coupled. For example, LF power and the LF/HF ratio decrease from wakefulness to non-REM (NREM) sleep; both of these parameters also increase during epochs of REM sleep (*24–26*). The blood collection procedure, by transiently increasing arousal, would be expected to change sleep-staging activity and hence alter HRV responsiveness. Thus, the blood collection procedure, which was unavoidable given the experimental design and primary goals of the studies reported by Sastre et al. (*10*), may have made it easier to unmask a subtle effect of magnetic field exposure because the blood collections, like the on–off field transitions during intermittent field exposure, were time-locked on the hour. If magnetic field exposure effects on HRV occur most readily when accompanied by some form of concomitant increase in physiologic arousal, persons with high chronic stress levels, or individuals with significant sleep problems (insomnia, sleep apnea, or restless leg syndrome), may be more likely to exhibit field-related changes in HRV. In this context, it would also be of interest to monitor HRV activity in workers in electrical occupations during and after performance of their routine work activities.

A biologic mechanism that could provide the necessary link between exposure to power-frequency magnetic fields and alterations in human physiology is not known. Cellular activity or function, however, may be modulated by the electric fields induced in the body by exposure to the ambient magnetic field. The biophysical issue here, of course, is whether the intensity of the generated magnetic field presented in the studies examined here is of sufficient strength to alter the endogenous electric fields generated by the heart. Calculations derived from the detailed whole-body dosimetric model of Dawson et al. (*27*) indicate that the 127.3-μT field would induce an average electric field of between 1.3 and 1.7 mV/m within heart muscle. This is far below the intensity of the endogenous fields measured in the heart of the dog, a well-accepted surrogate for the human heart. Hart and Gandhi (*28*) reported that these endogenous fields in the 40–70 Hz band range from 7.7 to 25 mV/m depending on the method of calculation used. Taken together, these reports indicate that direct excitation of the human heart, even by the 127.3-μT field, is extremely unlikely. Induced electric field effects on brain centers that control HRV, however, may still provide a plausible explanation for the results of Sastre et al. (*10*). Calculations indicate that the 28.3-μT field would induce an electric field of approximately 1.8 mV/m in cortical brain areas. This magnitude is above the documented threshold for electric field-induced alterations in cellular activity (*29*).

The failure to see an effect when comparing different field intensities may not be entirely surprising because the only high field intensity (127.3 μT) study in our data set is one in which blood was not collected. In a more recent study of independent-group design without blood collections (*30*), we again observed robust field-related suppression of the LF band of the HRV spectrum, and also of mean heart rate, when volunteers were exposed to circularly polarized magnetic fields at a frequency of 16 Hz and a resultant intensity of 28.3 μT. The 16-Hz frequency is well within the endogenous beta frequency band of the EEG. Exposure at this frequency may be more likely to induce an acute response because the beta frequency band exhibits a close temporal association with epochs of REM sleep and also shows a reciprocal relationship with delta activity during NREM sleep (*31*). These observations suggest that the lower intensity (28.3 μT) evaluated in the present series of exposure studies may be sufficient to alter the activity of the pontine and medullary brain centers that control HRV, provided that the neural substrate is responsive due either to an increase in physiologic arousal or to a closer match between the frequency of the exogenous magnetic field and endogenous neural activity. Further research to directly test this hypothesis could clarify whether the acute alterations observed in cardiac autonomic control mechanisms associated with the combination of physiologic arousal and magnetic field exposure have chronic health implications.

References and Notes

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