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ECG Changes in Humans Exposed to 50 Hz Magnetic Fields

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Abstract: ECG Changes in Humans Exposed to 50 Hz Magnetic Fields: Srdjan S. BORJANOVIC, *et al.* Institute of Occupational Health "Dr. Dragomir Karajovic", Serbia and Montenegro—Possible health issues of ELF EMFs include cardiovascular effects since both electrocardiogram and heart-rate changes have been reported in the literature. A non-linear relationship between field strength and biological response has been reported in some studies. In this study, a total of 59 subjects, divided into three independent magnetic field strength groups, were compared. A calculated 12-hour time weighted average (TWA) value of the fields was used as an exposure metric for each of the three locations ("low": 0.067 μT, "medium": 1.18 μT and "high": 5.2 μT) and subsequently used to estimate workers' exposure at these sites. Electrocardiograms were recorded in the resting position. Five parameters were derived from the ECG: heart rate (HR), duration of P wave and QRS wave, and duration of PR and QT intervals. The QT intervals were normalized to a heart rate of 60 (QTc). The obtained data were analyzed first by means of multivariate analysis of covariance and then oneway univariate analyses of covariances (ANCOVA) using exposure duration as a covariate. Only the ANCOVA on the QTc interval was significant. Our results suggest that the relationship between field strength and response is non-linear: the adjusted mean QTc values are similar between the "low" and the "high" group, but significantly lower in the "medium" group. One possible interpretation of our results is that a specific exposure pattern might be responsible for the non-linear effects observed, so that generally, characterizing exposure to electric and magnetic fields using simple metrics such as TWA may be insufficient.
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Among the possible health effects of exposure to extremely low frequency electromagnetic fields (ELF EMFs), cardiovascular effects have been reported in the database of EMF bioeffects. Studies of ELF EMFs and the cardiovascular system have generally focused on acute rather then long-term effects. Both electrocardiogram (ECG) changes and heart-rate changes have been reported in the literature. An increase in the amplitude of the T-wave signal in the rat electrocardiogram was observed during exposure to magnetic fields. This change, however, was the result of a superimposed electrical potential generated by aortic blood flow in the presence of the magnetic field[1]. The T-wave was affected rather than other components of ECG, since blood flows through the aorta during the period when ventricular repolarization is taking place. The increased T-wave voltage was unrelated to the electrical activity of the pacemaker area of the heart and the ECG change was simply a reflection of the coincident "magnetohydrodynamic" voltage generated by the blood flow in the presence of the applied magnetic field.

Investigators at one laboratory (Midwest Research Institute, Kansas City, Missouri., USA) have studied the effects of EMFs on the heart rate in humans for several years[1, 2]. According to their results, exposure to 60 Hz electric and magnetic fields resulted in a significant decrease of the heart rate. Field-related slowing of the heart rate was statistically significant for those subjects exposed first to the field and then to sham conditions. Those subjects exposed in the reverse order did not show significant slowing of the heart rate. In their most recent study[2], three matched groups of 18 men each participated in two 6 h exposure test sessions. After a sham exposure session, each group was exposed to a different level of combined electric and magnetic field: low group (6 kV/m, 10 μT), medium group (9 kV/m, 20 μT) and high group (12 kV/m, 30 μT). A significantly decreased heart rate was observed in the medium group, but not in the other groups. Also, for subjects exposed in the order field-sham, mean heart rate was significantly slower compared to sham exposure. The most important result of that paper was the greater latency from R to T wave in ECG found only in the medium group under field exposure for subjects who were exposed in the order field-sham.

The decreased heart rate mentioned above has rarely been replicated in different research laboratories as pointed out by Whittington *et al*.[3], who found no effect of a 50 Hz, 100 μT magnetic field (of several durations) on heart rate or blood pressure.

Research on the effects of ELF EMFs on human physiology has produced inconsistent results. This might be attributable to the low statistical power of published studies. A survey of the published investigations in this field showed that statistical power levels are very low, ranging from a mean of 0.08 for small effect sizes to 0.46 for large effect sizes[4]. In practice, this means that small effects of EMFs will remain undetectable due to low experimental sensitivity. Most, if not all, published studies have had little chance of detecting the small effect sizes likely associated with weak EMFs. The calculated statistical power reported in the study of Graham *et al*.[2] was 0.09, 0.34 and 0.65 assuming small, medium and large effect sizes respectively. To obtain sufficient power, researchers need to consider the sample size used, the statistical test employed, the alpha level, and the expected magnitude of the real effect. Whittington *et al*. state that if the statistical power of future EMF research is not sufficiently increased, the doubts and uncertainties over insignificant and unreproducible results will remain[4].

A static field effect on the heart rates of human subjects has been demonstrated by Jehenson *et al*.[5] Exposure to a 2 T field resulted in a 17% increase in cardiac cycle length; the values returned to pre-exposure levels within 10 min of exposure. Discussing the effect on the sinus node, the authors suggested it was probably harmless in healthy subjects, but pointed out that the safety of such exposure for patients with ECG rhythm disorders has not been determined.

Decreased heart rate after exposure to 50 Hz EMFs (up to 10.21 kV/m and 15.43 μT for several hours) has also been reported[6]. However, these findings could have been related to changes in the workload of the subjects.

Savitz and Loomis (1995) conducted a large historical cohort mortality study among electric utility workers in the United States with at least 6 months of work experience. Exposure was estimated by linking individual work histories to data from worksite magnetic field measurements. Death rates were analyzed in relation to magnetic field exposure history with Poisson regression. The mortality from "diseases of the heart" was lower than anticipated on the basis of general population rates (standardized mortality ratio 0.76) although it could have been due to a "healthy worker effect" in which employment selection leads to lower mortality rates as compared to that of the general population[7].

There were three steps of the research undertaken in this study. The first was to measure the strength of the magnetic field produced by power transformer stations. The second step was to use these magnetic field data and additional data collected on the patterns of exposure to estimate subjects' TWA exposure in power transformer stations. The final step was to determine whether the exposure levels exhibited dose-response patterns that might influence the examined ECG intervals and waveforms.

Procedures and Methods

A number of transformer substations in urban parts of Belgrade were initially subjected to a walkaround inspection, in order to determine suitable locations for representative measurements. This inspection included a brief survey of magnetic field levels with a Wandel-Goltermann EFA-3® instrument. Three examination sites were selected (labeled Locations 1, 2 and 3), based on several criteria: similar number of exposed subjects in each group, expected TWA exposure levels significantly different between groups, traceable working and behavioral habits of workers, similar working schedules, readily accessible workers' medical and working histories. The locations correspond to three different transformer substations.

The subjects were transformer substation workers employed by the Municipal Light & Power Utility Company. All were male, in good health, and had had an education beyond high school. Their work tasks and practices included maintenance, control, measurement, testing, and installation of equipment associated with transformer substations. The mean age of the subjects was 41.8 ± 9.4 yr (SD), with a mean exposure duration of 17.7 ± 10.8 yr (SD). Subjects with exposure durations of less than 5 yr were not included in the study. Most of the subjects worked 12-h shifts. The work is, thus, divided in two shifts per day. The exposure correction of those workers with a shorter (8-h) shift was accounted for as described later. The facilities included dormitory rooms, where the workers typically spend an average of 7 h per night, sleeping. Their tasks are performed interchangeably, meaning that each task can be performed by any of the workers. Inspection and measurements were performed directly at the workplaces in such a manner as to minimally interfere with the daily routine.

Three independent field strength groups with a total of 59 subjects were included in the study. These were selected from a total of 105 workers (32 at Location 1, 33 at Location 2 and 40 at Location 3). A number of workers were removed from the study as a result of lacking or inadequate background information, or presence of other health issues that may interfere with the results. The low exposure group, stationed at "Location 1", comprised 20 workers who were engaged in assembling new substations and were therefore assumed to be exposed to field levels comparable to the natural background. The medium exposure group consisted of 19 substation operators from a power transformer substation "Location 2". The high exposure group was composed of 20 high voltage substation workers from another power transformer substation "Location 3". Both "Location 2" and "Location 3" substations include two sections, 35/10 kV high voltage and 10kV/380V low voltage.

In most cases, it was difficult to directly determine the amount of past cumulative exposure to magnetic fields, prior to employment in the observed transformer substations. Instead, a complete occupational history was taken into account. Past exposure assessment was made for every subject based on exposure duration of every job type and a standard exposure level for each job type. The factor considered to have the most effect on an individual's cumulative personal exposure was the amount of time spent on particular work tasks with high exposure. Persons whose records showed a history of employment on tasks involving high magnetic field levels for long (over 1 yr) but insufficiently well documented periods of time, were excluded from the study. Six subjects, who were previously working in one of the other two observed transformer substations (Location 2 or Location 3) for a known period of time, were moved from the low exposure group to the medium or high exposure groups. A further five subjects were excluded from the statistical analysis due to missing data about their past exposure duration, resulting in 20, 19 and 20 subjects in the low, medium and high exposure groups, respectively.

In each of the three locations, a local "map" of magnetic field distribution was created as follows. In each particular location, a number of spots were selected for spot measurements. These spots corresponded to places where the workers spent relatively large intervals of time and those where the initial walkaround inspection revealed high magnetic field levels. Local magnetic fields at these spots were determined by repeated measurements and averaging: at each spot *i*, 12 results were taken at 10 s intervals, and averaged. The value obtained in this manner was labeled B_i.

A 12-h time weighted average (TWA) value of the 50 Hz magnetic fields was selected as an exposure metric. In each of the three locations examined, the TWA value was calculated as the sum of local magnetic field strengths at measurement spots B_i multiplied by a weighting parameter w_i, over all N spots where the measurements were made, as in the following formula:

$$TWA=\sum_{i=1}^{N} w_i \, |\overline{B}_i| \qquad (1)$$

The weighting parameter represents the time fraction a worker spent (daily, on average) on a particular spot *i*. Since the workers observed in each of the three substations perform routine tasks interchangeably (i.e. each maintenance task, on a particular spot, can be performed by any of the workers), the long term exposure of any particular worker in an observed group in a particular substation is assumed to be similar to the exposure of any other worker within that group. Given this assumption, the estimation of long term exposure can be performed by observing the tasks at certain spots. This can be represented as:

$$w_i = \frac{t_i}{12\ \mathrm{h}} \cdot \frac{n_{wi}}{N_w} \qquad (2)$$

where t_i is the average duration of the task, 12 h is the shift duration, n_{wi} is the number of workers typically engaged on the task in question, and N_w is the total number of workers observed. Hence, for example, if a routinely performed task number i=27 requires n_{w27}=3 workers to work for t_{27}=30 min every day, and the total number of maintenance workers is N_w=20, then w_{27}=(30 min/12 h) × (3/20)=0.00625. It is now possible to claim that, when assessing long term exposure, any one of the observed group of workers spends a fraction of time equal to w_{27} on the particular spot i=27. The w_i values determined in this manner were subjected to corrections due to vacations and other absences, irregularities in performing certain tasks (such as tasks not performed on daily basis) etc. Data for these corrections were obtained through interviews with workers and substation foremen or leadmen, from records, or direct observations. It should be noted, however, that the term "task", as used here, actually represents a worker's action taking place on a certain spot *i*. Thus, each task corresponds to a certain spot (for example, taking a certain reading always takes place on the same spot *i*, and always takes a single worker). Hence, the term "task" does not involve only maintenance operation tasks, but also certain recreational activities, eating, resting (watching TV) etc.

The described method allows an estimation of the time fraction an average worker spends at different spots. Only those w_iB_i products that significantly contributed to the total sum were taken into account, and the corresponding w_i parameters received the greatest attention in their determination. The spots where workers spend very little time such as corridors and locker rooms (and, hence, the corresponding w_i parameters are small) were not included in the sum. Other spots where the w_iB_i product was small due to small B_i, were also excluded, assuming they would contribute very little to the TWA. Any differences in working schedules were compensated for by introducing a correction of the exposure by normalization to the longest duration of the work shift (12 h). This was

Table 1. Estimated TWA levels and ECG parameters

	Location 1 (TWA_{LOW}=0.067 μT) "Low exposure"	Location 2 (TWA_{MED}=1.18 μT) "Medium exposure"	Location 3 (TWA_{HIGH} = 5.2 μT) "High exposure"
Heart rate (min^{-1})			
Mean	73.5	74.9	75.8
Std. Dev.	6.7	12.1	9.6
P wave (s)			
Mean	0.111	0.114	0.115
Std. Dev.	0.029	0.014	0.017
PR interval (s)			
Mean	0.15	0.13	0.16
Std. Dev.	0.05	0.04	0.02
QRS interval (s)			
Mean	0.077	0.076	0.071
Std. Dev.	0.013	0.007	0.01
QTc interval (s)			
Mean	0.391	0.370	0.396
Std. Dev.	0.027	0.025	0.022

accomplished by calculating the corresponding w_i factors assuming a 12-h interval, even in cases where the shift lasted for shorter periods, and assuming the rest of the time the workers were exposed to a background level of magnetic fields. For the background level, a TWA value obtained in the lowest exposure group was taken.

It is important to note that the method described, was not used to estimate workers' exposure on an individual basis, since such results would be highly inaccurate. Rather, the TWA estimates were used to form well contrasted exposure groups with similar working histories, but working in conditions with large differences in magnetic field exposure.

All measurements were made using the Wandel-Goltermann EFA-3® instrument with an isotropic probe. This instrument is capable of taking simultaneous 3-axial measurements of ELF magnetic fields and providing a RMS vector magnitude of the magnetic flux density. The magnetic fields obtained in this manner were used in calculating the TWA values. Spot measurements were performed at 1.5 m height from ground. All measurements were performed while the substations were working at nominal loads.

Electrocardiograms were recorded in the resting position at the Occupational Health Centre of the Utility Distribution Company during a periodical check-up. Five parameters were derived from the ECG: heart rate (HR), duration of P wave and QRS wave, and duration of PR and QT intervals. The QT interval varies with the heart rate and must be corrected (QTc). This was done using the Bazelt equation which gives the QTc for a heart rate of 60[8].

The obtained data were analyzed with SPSS software version 11.5 using analysis of covariance.

Results

The estimated TWA levels of the three exposure groups and the means and standard deviations of analyzed ECG parameters for the three groups are shown in Table 1.

A one-way multivariate analysis of covariance (MANCOVA) was conducted to determine the effect of the level of exposure to ELF EMFs ("low", "medium", "high") on the five ECG parameters using individual exposure duration (in years) as the covariate. Since the multivariate F statistic just approached significance (Wilks' Λ=0.693, F (10, 92)=1.80, p=0.071, partial η^2=0.16), one-way univariate analyses of covariances (ANCOVA) on each of the ECG parameters were conducted as follow-up tests to the MANCOVA. Providing adjustment with respect to exposure duration (in years) only the ANCOVA on the QTc interval was significant (F (2,50) = 4.40, p=0.017, partial η^2=0.15). The adjusted mean QTc values, obtained through the ANCOVA procedure, were 0.388 s, 0.368 s and 0.392 s for the "low", "medium" and "high" group, respectively. Post hoc comparisons of adjusted mean QTc values among groups (using the Least Significant Difference method) revealed significant differences between the "low" vs. "medium" groups and between the "medium" vs. "high" groups, but not between the "low" and "high" groups, as shown in Table 2.

Although observed changes in PR intervals showed a similar trend to QTc values, statistical analysis revealed no significant differences among the adjusted PR means.

Table 2. The results of the post-hoc multiple comparisons (Least Significant Difference Method) of adjusted mean QTc values among groups

Compared Groups	Mean Difference	Standard error	95% Confidence Interval for Difference
"Low exposure" vs. "Medium exposure"	0.02	0.009	(0.001– 0.038)
"Low exposure" vs. "High exposure"	–0.004	0.009	(–0.023 – 0.014)
"Medium exposure" vs. "High exposure"	–0.0240	0.009	(–0.041 – –0.007)

No other statistically significant effects were observed in the examined ECG parameters.

Discussion

A simple dose-response model relating peak or TWA magnetic field exposure in power transformer stations would require that increasing field strength is associated with increased adjusted QTc interval duration values. Our data are not consistent with this picture. Our results imply that the relationship between field strength and response is non-linear. Namely, the adjusted mean QTc values are similar between the "low" (0.388 s) and the "high" (0.392 s) group, but significantly lower (0.368 s) in the "medium" group.

In this context our findings are similar to the results of Graham *et al.*, who performed a study to test the hypothesis that, in humans, biological responses are dependent on exposure at specific levels of field strength and to explore whether the relationship between the field strength and response might differ for different end-points[2]. The exposure levels described in their paper were comparable in magnitude to the range of field strengths associated with power substations in our study. They found a significantly decreased heart rate and an increase in latency from R to T wave in ECG in subjects from the medium group (9 kV/m, 20 μT, 6-h exposure). The authors suggested that field effects were related to changes that occur during the repolarization phase of the cardiac cycle, an interval during which changes in calcium ion flux are most likely to have effects. Thus changes in calcium ion flux could be one mechanism by which field-related changes occur. One of their conclusions was that the relationship between field strength and response might be non-linear and that the dose-response relationship differs for different end-points. Such results may indicate that more than one mechanism might be involved in producing an intensity "window".

Although our results suggest a non-linear dose-response relationship as was the case in the study of Graham *et al.*, the results cannot be directly compared since their previous study utilized a controlled short-term exposure approach and our study is concerned with ECG changes in an uncontrolled long-term exposure environment.

The mechanisms by which power frequency fields affect the cardiac rhythm are not yet understood. Cardiac control mechanisms that might be responsible for field-related changes of the QT interval are also not known. Schwartz *et al.* reported a field-dependent increase in the efflux of Ca^{2+} ions in isolated frog hearts exposed to a VHF field which was amplitude-modulated at 16 Hz. The increase was about 18% at 0.3 mW/kg and 21% at 0.15 mW/kg[9]. Findings that suggest a non-linear dose-response relationship and an intensity "window" effect of ELF field-induced efflux of calcium ions from brain tissue *in vitro* were reported by Blackman *et al.*[10, 11] The EMF and the interaction sites in the membrane have been considered to elicit modifications of Ca^{2+} binding to glycoproteins along the external membrane surface and this process produces changes in calcium ion efflux[12].

One possible interpretation of our results is that a specific exposure pattern might be responsible for the results observed. The working environments of the three examined exposure groups ("low", "medium" and "high") were situated in three different physical locations. In these locations, the subjects' TWA exposure was estimated based on spot measurements of magnetic fields and their observed activities, as described above. However, the complexity of electromagnetic fields is rarely taken into account, as was the case in this study. For power frequency EMFs, the exposure is always in near field conditions, indicating a complex spatial field distribution. Exposure in a certain order (as a worker moves from spot to spot, changing his body's relative position to a time-varying magnetic field vector) might also be responsible for non-linear dose-response effects, which might lead to the conclusion that TWA, as a single number, is an inadequate parameter to describe ELF EMF exposure. In addition, certain spots may exhibit strong switching transients which the ELF measurement equipment is incapable of handling.

Unfortunately, it was not possible to further evaluate this hypothesis based on the data collected, because individual "vector" doses were not measured. One should be aware that identical average exposures (TWA) may mask important differences in the temporal patterns of exposure. In the design of future research, it would be prudent to use individual magnetic field dosimeters, capable of simultaneous triaxial measurements, to try to establish whether the specific exposure pattern is linked to observed effects. In addition, improving the methodology for past and non-occupational exposure assessment and accounting for various confounders as well as noise introduced by background exposure is essential. Further research is needed to examine whether the observed changes in the QTc interval are simply a downstream reflection of more important changes occurring in other parts of cardiovascular system. No etiological relation to EMF can be established in the absence of additional experimental evidence using both animal models and human subjects. However, the only way to seriously evaluate the real risks of occupational ELF exposure in general is through elucidation of the interactions and effects at the molecular level.

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