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Analyses of magnetic-field peak-exposure summary measures

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Two previous epidemiologic studies reported an association between the maximum magnetic field exposure logged during a 24-h measurement period and risk of miscarriage. A hypothesis was put forth which argued that the observed association may be the result of behavioral differences between women with healthy pregnancies (less physically active) and women with miscarriage. We analyzed four existing data sets with power–frequency magnetic-field personal exposure (PE) measurements to investigate the characteristics of peak-exposure measures. We found that the value of the measured maximum magnetic-field exposure varied inversely with the sampling interval between magnetic-field measurements and that maximum values demonstrated less stability over time in repeated measurements, compared to time-weighted average and 95th and 99th-percentile values. We also found that the number of activity categories entered by study subjects could be used to estimate the proportion of subjects with exposure above various threshold values. Exposure metrics based on maximum values exceeding thresholds tend to classify active people into higher exposure categories. These findings are consistent with the hypothesis suggesting that the association between maximum magnetic fields and miscarriage are possibly the result of behavioral differences between women with healthy pregnancies and women who experience miscarriages. Thus, generalization from a given study to more global exposure characterization should be made with particular caution and with due consideration to sampling interval and other characteristics of the measurement protocol potentially influencing the measured maximum. Future epidemiologic studies of peak magnetic field exposure and spontaneous abortion should carefully evaluate the potential confounding effect of the women's activity level during pregnancy.
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Introduction

During the past two decades a number of epidemiologic studies have investigated whether maternal exposure to power–frequency electric and magnetic fields (EMF) is associated with an increased risk of adverse pregnancy outcomes, including birth defects and spontaneous abortions (SAB) (Shaw, 2001). In 1998, the National Institute of Environmental Health Sciences (NIEHS) Working Group concluded that there was inadequate evidence to suggest that maternal environmental or occupational exposure adversely affects pregnancy outcomes (Portier and Wolfe, 1998). In 2001, another major evaluation of the epidemiologic literature on EMF and health by the Standing Committee on Epidemiology of the International Commission on Non-Ionizing Radiation (ICNIRP) concluded that the available evidence did not support the hypothesis that maternal exposure to residential or occupational EMF was associated with adverse pregnancy outcomes (Ahlbom et al., 2001; ICNIRP, 2003).

However, two epidemiologic studies from California (a nested case–control study and a prospective cohort study), published at the same time in early 2002, revived interest in the area (Lee et al., 2002; Li et al., 2002). Both studies examined the relation of 24-h personal magnetic-field exposure to SAB risk among pregnant women. Both reported an association between measured maximum magnetic-field exposure and increased SAB risk. Maximum was defined as the single highest reading in a 24-h time series of readings taken, in the case of these two studies, every 10 s. However, neither study provided strong support for an association between miscarriage and time-weighted average (TWA) magnetic-field exposure.

The basis for the association found in the California studies remains uncertain. In a commentary published with the studies, Savitz (2002) argued that it is plausible that the findings resulted from differences in "micromobility" between women who had healthy pregnancies and women who miscarried. Savitz (2002) hypothesized that owing to their size, awkwardness, and lowered energy level, and to nausea and vomiting, women with healthy pregnancies would tend to move around less, and would therefore be less likely to encounter high magnetic fields than women who already had or were destined to have miscarriages.

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Past emphasis in magnetic-field exposure assessment and exposure characterization for epidemiologic purposes has been on measures of central tendency such as long-term TWA exposure. The two California studies used maximum measured magnetic field as a primary exposure metric, a metric not commonly used in previous epidemiologic studies. The results reported in these studies precipitated our interest in maximum magnetic field and other magnetic-field peak-exposure measures. As opposed to long-term TWA exposure, the maximum exposure during a 24-h period represents a single measurement, is very dependent on location and activity, and is difficult to measure accurately. Thus, the maximum was presumed to be an unstable indicator of an exposure of short duration.

The analyses reported herein were conducted to further our understanding of the nature of magnetic-field peak-exposure measures. We utilized four existing data sets with personal exposure (PE) measurements to investigate the characteristics of magnetic-field peak-exposure metrics. Specifically, we investigated the dependence of peak-exposure metrics on sampling interval, the consistency of peak-exposure measures across data sets, and the temporal stability of peak-exposure measures in the home. We also modeled the dependence of maximum exposure during the day on the number of different activity categories that were experienced.

Methods

Exposure Data Sets

Exposure data sets were available from four previous studies: the Kaiser SAB Study (Li et al., 2002), the EPRI Long-Term Wire-Code (LTWC) Study (Rankin et al., 2002), the EPRI Household Appliance Use Study (Mezei et al., 2001), and the US Department of Energy RAPID Program 1000-Person Study (Zaffanella and Kalton, 1998). The set of common activity categories used for all data sets was comprised of: 24-h, Home (not in bed), In-bed, Work, Travel, and Others. PE measurements during the EPRI LTWC Study were restricted to the home. Consequently, this data set only includes data in the home and In-bed categories. Descriptions of the subjects, dates and instrumentation for each study are summarized in Table 1.

Kaiser SAB Study Data Set The Kaiser SAB Study data set represents 24-h magnetic-field PE data from 1043 pregnant women in the San Francisco region. Each participant wore an EMDEX II exposure meter (Enertech Consultants, Campbell, CA, USA) sampling at 10-s intervals. The women kept an activity diary. In all, 151 subjects' exposure data were excluded from the analyses due to inconsistencies between patterns of exposure data and reported activity or for missing diary information, leaving 892 subjects for analysis.

In addition to the 24-h exposure and activity data, participants were also interviewed to obtain demographic and lifestyle information. This latter information and their health-outcome status (normal pregnancy or SAB) were not available for the analyses presented here.

An extensive presentation of exposure summary measures from the Kaiser SAB Study by activity category, and by electrical system and neighborhood parameters without

Table 1. Summary of studies with magnetic-field personal-exposure measurements.

Study	Dates/location	Subjects	No. of subjects	PE meter			Activity categories
				Model	Sampling interval (s)	Range, (mG)	
Kaiser SAB[a]	10/96–10/98 San Francisco area	Pregnant women	892	EMDEX II	10	3000	24-h, Home, In-bed, Work, Travel, Other
EPRI LTWC[b]	1/94–6/97 8 regions of United States	Adults at home	218 houses, 825 visits	EMDEX II	10	3000	Home, In-bed
EPRI Appliance[c]	4/96–9/96 San Francisco Peninsula	Adult couples	162 (81 couples)	EMDEX Lite	4	700	24-h, Home, In-bed, Work, Travel, Other
RAPID 1000-Person[d]	11/97–4/98 Random sample of United States	Male and female adults	1012	EMDEX PAL	0.5 s with 10-min summary	1000	24-h, Home, In-bed, Work, Travel, Other

[a] Li et al. (2002).
[b] Rankin et al. (2002).
[c] Mezei et al. (2001).
[d] Zaffanella and Kalton (1998).

reference to demographics, lifestyle or health outcome is available from the California Department of Health Services (Bracken, 2002).

EPRI LTWC Study Data Set The LTWC data set is comprised of PE and long-term fixed location measurements collected at home by residents of 218 single-unit detached dwellings throughout the United States. Measurements were conducted at each home during up to four visits spread over up to 20 months. Visits were typically 2–3 days long resulting in a mean PE data collection period of 33.5 h during a total of 825 visits. Residents recorded their location or activity in the home environment in a diary while they wore an EMDEX II meter sampling at 10-s intervals.

The sampling frame was based on Wertheimer-Leeper wire-code category and over sampled high wire-code categories, which tend to have higher fields (Kheifets et al., 1997). Previous analysis emphasized measures of central tendency for PE measurements and comparisons between different types of measurement by wire-code category. Detailed descriptions of the study design and protocols plus additional analyses, and key results are published elsewhere (Bracken et al., 1998; Rankin et al., 2002).

EPRI Household Appliance Use Study Data Set The Appliance Use Study characterized magnetic-field exposures during daily activities and during household appliance use. The data set represents 162 participants in the study (81 couples) from three cities on the San Francisco Bay Peninsula (Palo Alto, Menlo Park, and Redwood City, CA, USA).

Participants wore an EMDEX Lite meter (Enertech Consultants, Campbell, CA, USA) sampling at 4-s intervals for a nominal 24 h. The study subjects recorded their activities and appliance use in a diary.

The previously reported analysis emphasized total integrated exposure and the contribution to it from specific activities and appliances. Fields tended to be higher at work and during use of certain appliances. However, the contribution to overall exposure of appliance use was not significant except for computer use (Mezei et al., 2001).

RAPID Program 1000-Person Study Data Set The 1000-Person Study characterized exposures for 1012 randomly selected male and female subjects throughout the United States. Participants received by mail an EMDEX PAL meter (Enertech Consultants, Campbell, CA, USA) with instructions and were asked to complete a contemporaneous activity diary over the 24-h measurement period. Participants also provided demographic and occupational data.

The PAL meter sampled at 0.5-s intervals and accumulated data for 10 min before summarizing them for storage. Among the summary measures stored were maximum, 99th percentile, 95th percentile, and time spent above certain thresholds. Summaries for a 24-h period or for time in an activity category were computed from the 10-min records.

This study compared exposures across gender, age, activity category, geographical region, and other parameters. As with the previous data sets, these analyses tended to stress TWA exposures over a day or other time period.

Examination of the RAPID 1000-Person data set indicated that the times in upper field bins (say, time with field >32 mG) were sometimes zero when the measured maximum exceeded the bin threshold. Discussions with the original investigators identified the source of the problem as rounding times less than 30 s to zero. Records where this had occurred were corrected by inserting 30 s or less in the bin that was previously zero. Another discrepancy in the data set was manifest by zero values for the 99th percentiles in a few records. This was not resolved with the original investigators and the six records with this problem were excluded from analyses involving the 99th percentile.

Data Analyses

To facilitate analysis and provide compatible results from all data sets, a common set of summary measures, called peak-exposure measures, were generated for each data set. This was accomplished easily for the three data sets with time-series data. However, the 10-min data summaries for the RAPID 1000-Person Study were not as amenable to achieving a compatible set of summary measures. The maxima for the 24-h and for the other categories represented true maxima because they are derived from a single measurement that is recorded in the 10-min summaries. However, percentiles could not be accurately computed based solely on the available 10-min summary measures. Therefore present analyses relied on the aggregate percentiles previously estimated by the original researchers (Zaffanella and Kalton, 1998).

The peak-exposure measures common to all data sets were the maximum, and the 99th percentile to describe the magnitude of the peak field; the fraction of measurements (or proportion of total time) above 8, 16, and 32 mG to quantitatively describe exposure above a threshold; and the presence of measurements above 8, 16, and 32 mG to serve as a binary indicator of peak exposure above a threshold.

During collection of PE data, the subjects recorded their location/environment by time-of-day in a diary. This allowed the PE measurement data to be linked with time/location activity categories such as 24-h, home, and work. PE measurements were summarized by individual period in an activity category, by accumulated time in a category during a measurement period, and for the 24-h category. We analyzed the measurements accumulated by category and by entire measurement period.

The LTWC Study data included only measurements in the home and In-bed categories and therefore could not provide 24-h data. Summary measures for the LTWC data were drawn from the 218 first visits to a house, except for temporal stability analyses between visits.

The different meters used in the four studies had different sampling intervals. Time-series data collected by the EMDEX II and EMDEX Lite meters used in the Kaiser SAB, LTWC and Appliance Use studies were amenable to analysis by sampling interval, whereas the 10-min summaries generated by the EMDEX PAL used in the 1000-Person Study were not. To examine the effect of sampling interval, summary measures simulating longer sampling intervals were produced from the base 4- or 10-s interval up to intervals of several hundred seconds by excluding increasing numbers of intermediate measurements from the original time series. Emphasis was on the maximum and 99th-percentile summary measures. The 24-h data including all categories were used for the Kaiser SAB and Appliance Use studies. Data from the home and in-bed categories were combined into a home-all category for the LTWC Study.

The analyses investigated the robustness of the maximum, above threshold, and other peak metrics to several parameters, including sampling interval of the PE meter, time between 24-h samples and the number of activities during a day. Special emphasis was placed on the presence of maximum above a specified threshold metric because of its uniqueness in requiring only one "high" measurement to be classified as exposed in the two epidemiologic studies of primary interest (Lee et al., 2002; Li et al., 2002).

The analyses were performed using the *R* statistical software (www.r-project.org). Data were analyzed using descriptive statistics, statistical inference tests, and measures of association. Both parametric and non-parametric statistical tests were used.

Activity-Related Exposure Model The maxima above threshold are accumulated as a subject passes through different activity categories during a day. A simple model for such exposures assumes that the distributions of maxima within each category are independent and that the observed fraction of the exposed subjects within each category is the value recorded for each data set (see later in Table 3). The model also assumes that if sufficient time is spent in a category then the maximum is unrelated to time spent in the category. In this model, the probability of a subject being exposed to fields above 16 mG increases as the subject experiences time in different activities. Thus, the number of subjects with exposures above a given threshold, such as 16 mG, accumulates incrementally as the number of experienced activity categories increases. This model was compared to observations from the Kaiser SAB Study data.

Results

Effects of Sampling Interval

An instrument recording a time series of measurements at finite intervals will not necessarily capture the same maximum field over a measurement period as a "peak-hold" instrument will. The EMDEX meters used in these studies employed discrete interval sampling with each 3-axis sampling sequence taking about 0.2 s. The true maximum may not be captured during this finite sampling period and it may occur between samples in the time series. Furthermore, because the recorded value is the average of values sampled during an approximately 0.2 s window, a maximum that lasts less than 0.2 s will be diluted by the surrounding measurements. The more frequent the measurement the more likely the true maximum will be estimated, or even captured. Thus, the maximum for an individual recorded by one meter may not be equivalent in absolute terms to that recorded by another meter with a different sampling rate.

Box plot representations of the distributions of the maximum and 99th-percentile summary measures from the 892 Kaiser study subjects are plotted *versus* sampling interval in Figures 1 and 2, respectively. As the sampling interval becomes longer in Figure 1, the distributions of maxima tend to move toward lower fields. The linear relationship between the descriptors of the maximum distributions and sampling interval suggests an inverse power-law relationship. Figure 2 shows that the distributions of the 99th-percentile measure were not dependent on sampling interval. TWA was also unrelated to the sampling interval (not shown).

The apparent linear relationship between the logarithms of the maximum distribution descriptors and the sampling interval (Figure 1) can be expressed as: $ln(B_{\max}) = a\ ln(\Delta t) + c$, where, $B_{\max}$ is the maximum distribution descriptor

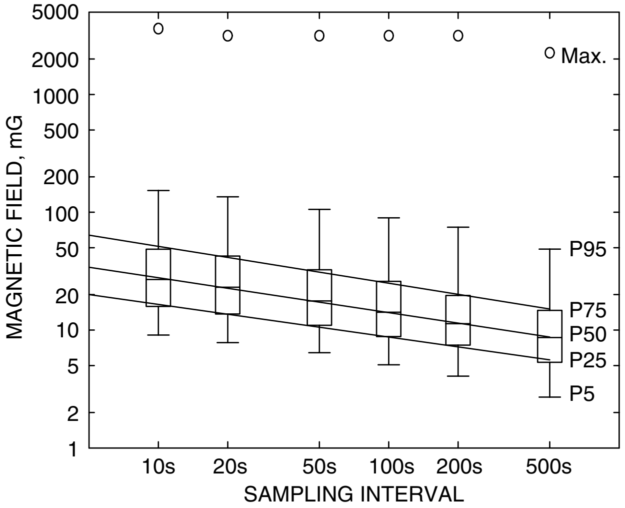

Figure 1. Distributions of 24-h maxima of magnetic-field PE measurements *versus* sampling interval for Kaiser SAB Study.

(25th, 50th, or 75th percentile), Δt is the sampling interval, and a and c are constants describing the slope and intercept of the linear model. Taking the anti-log of both sides of this expression yields: $B_{\max} = (exp)^c\ (\Delta t)^a$.

The values for slope and intercept parameters for the Kaiser SAB Study were determined from linear regression of the points at each sample interval for the 25th, 50th, and 75th percentile descriptors in Figure 1 and for similar data from the other studies. The results for the 25th percentile and median maximum distribution descriptors and for the median 99th-percentile distribution descriptor are given in Table 2 for three studies.

The range of the distributions of maxima for all three studies increases as the sampling interval decreases, following an inverse power-law with exponent a ≈ −0.30. For example, in the Kaiser SAB Study the 25th percentile of the maximum goes from 13 mG at a 20-s sampling interval, to 16 mG at a 10-s interval, to an estimated 21 mG at a 4-s interval. The corresponding adjusted maximum values for the 25th percentile in the Appliance Use study are 14, 17, and 22 mG for 20-s, 10-s, and 4-s intervals, respectively.

The fitted lines for the 99th-percentile distribution descriptors in Figure 2 have slopes of very near zero. Thus the distribution of the 99th percentiles is constant with sampling interval, as are those for the 95th percentile and TWA (not shown).

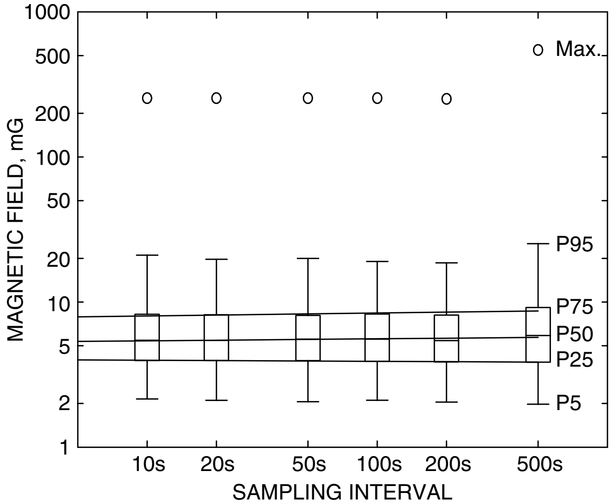

Figure 2. Distributions of 24-h 99th percentiles of magnetic-field PE measurements *versus* sampling interval for Kaiser SAB Study.

Comparison of Peak-Exposure Measures between Studies

The distributions of the maximum, 99th-percentile and TWA values for the 24-h period in three studies are shown in Figure 3. There is considerable overlap between the measures from the different studies. However, the distribution of the 24-h maxima tended to be highest in the 1000-Person Study followed by the Appliance Use Study, while lower maximum values tended to be recorded in the Kaiser SAB Study. Owing to the large number of observations in the individual studies, non-parametric tests for all pairwise and overall comparisons yielded statistically significant results. The observed trend in the distributions of the 24-h maxima is consistent with an inverse relationship between the length of sampling interval used in the studies and the observed magnitude of maximum values.

No similar trend across studies was seen for the 24-h 99th-percentile and TWA values. In fact, higher 99th-percentile and TWA values tended to occur in the Kaiser SAB Study, and lower values were recorded in the 1000-Person Study. The lower values in the 1000-Person Study may be related to the unknown methodology for determining 99th percentile in that study or to study location. The Kaiser SAB Study was conducted in an urban area in and around San Francisco, while the 1000-Person Study included a random sample of the US population including more people living in rural areas with a tendency of lower average exposure. Similar patterns between studies could be observed for the distribution of maximum, 99th-percentile and TWA values when only home or work exposures were considered (data not shown).

The fraction of subjects with at least one measurement above specific threshold values is shown in Table 3. The Appliance Use and 1000-Person studies tended to have larger fractions above thresholds than did the Kaiser SAB and the EPRI LTWC studies. This was especially the case for higher thresholds, and is consistent with the higher maximum values recorded with faster sampling instruments. When maximum values in the Appliance Use Study were adjusted to a 10-s sampling interval, the fraction of subjects with exposures

Table 2. Constants for fitted linear model for percentiles of distributions of maxima and 99th percentiles by sampling interval (Δt) by study: $B_{\max} = e^c\ (\Delta t)^a$.

Study	25th percentile of distributions of maxima		Median of distributions of maxima		Median of distributions of 99th percentiles	
	Slope, a	Intercept, c	Slope, a	Intercept, c	Slope, a	Intercept, c
Kaiser 24-h	−0.28	3.44	−0.30	4.01	0.014	1.68
LTWC Home-All	−0.31	3.04	−0.27	3.42	0.002	1.08
Appliance Use 24-h	−0.27	3.47	−0.32	4.15	−0.003	1.58

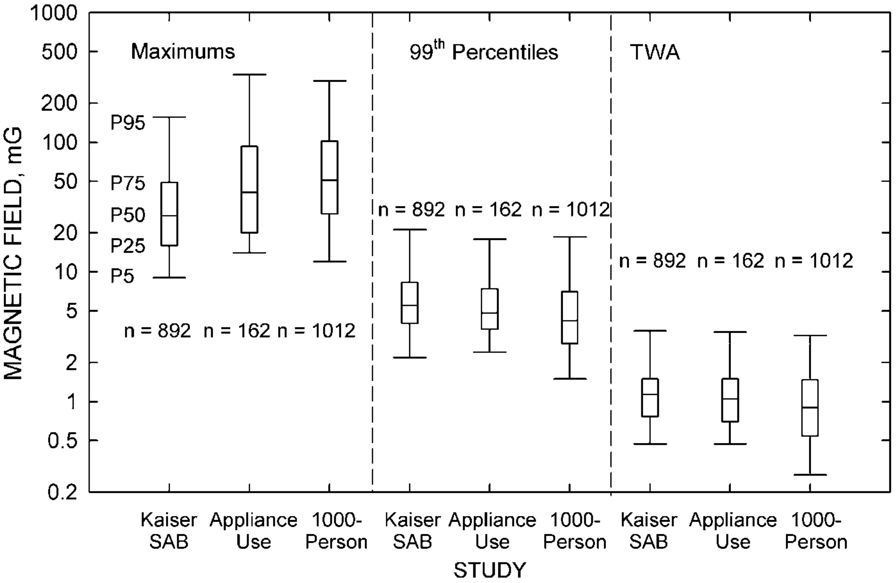

Figure 3. Box plots of maximum, 99th-percentile summary measures, and time-weighted average (TWA) for 24-h magnetic-field PE measurements by study

Table 3. Fraction of subjects with at least one measurement exceeding threshold in selected activity categories by study.

Activity	Threshold	Fraction in category with measurements exceeding threshold			
		Kaiser SAB	LTWC PE	Appliance use[a]	1000-Person
24-h	N	892	N/A	162	1012
	>8 mG	0.97	N/A	0.99 (0.98)	0.98
	>16 mG	0.75	N/A	0.90 (0.74)	0.92
	>32 mG	0.43	N/A	0.59 (0.48)	0.70
Home	N	890	218	153	1006
	>8 mG	0.67	0.82	0.92 (0.88)	0.82
	>16 mG	0.34	0.46	0.70 (0.56)	0.63
	>32 mG	0.15	0.24	0.40 (0.32)	0.40
In-Bed	N	869	207	142	995
	>8 mG	0.15	0.11	0.19 (0.15)	0.19
	>16 mG	0.04	0.02	0.09 (0.08)	0.10
	>32 mG	0.01	0.00	0.05 (0.03)	0.05
Work	N	570	N/A	47	526
	>8 mG	0.73	N/A	0.77 (0.68)	0.88
	>16 mG	0.39	N/A	0.60 (0.49)	0.70
	>32 mG	0.18	N/A	0.36 (0.28)	0.46
Travel	N	806	N/A	N/A	765
	>8 mG	0.83	N/A	N/A	0.79
	>16 mG	0.39	N/A	N/A	0.49
	>32 mG	0.18	N/A	N/A	0.23
Other	N	658	N/A	143	665
	>8 mG	0.60	N/A	0.85 (0.75)	0.67
	>16 mG	0.29	N/A	0.56 (0.39)	0.43
	>32 mG	0.14	N/A	0.24 (0.17)	0.18

[a] Values in parentheses are adjusted to 10-s sampling interval.

Table 4. Fraction of subjects in Kaiser SAB Study exposed to maximum field exceeding 16 mG by number of activity categories.

Number of activity categories in group[a]	Observed			Cumulative model	
	Number in group	Number exposed >16 mG	Fraction of group with >16 mG	Number exposed >16 mG	Fraction of group with >16 mG
2	42	20	0.48	15.5	0.37
3	91	60	0.66	54.8	0.60
4	359	265	0.74	245.8	0.69
5	400	320	0.80	333.0	0.83
All subjects	892	665	0.75	649.1	0.73

[a] Group with two activity categories: Home + In-bed (40), Home + Other (1), In-bed + Other (1); Group with three categories: Home + In-bed + Work (9); Home + In-bed + Travel (41); Home + In-bed + Other (32); Home + Work + Travel (1); Home + Travel + Other (7); Work + Travel + Other (1); Group with four categories: Home + In-bed + Work + Travel (143); Home + In-bed + Work + Other (3); Home + In-bed + Travel + Other (200); Home + Work + Travel + Other (13).

above the given thresholds was much more compatible with those observed in the Kaiser SAB Study (10-s sampling interval).

Accumulation of Daily Maximum by Activity/Location

As subjects moved through their day the number of activities they encountered served as a measure of overall activity level. The effect of this measure of activity level on exposure to maximum fields greater than 16 mG was examined for the Kaiser SAB Study data (Table 4). (Maximum exposure above 16 mG was used in the Kaiser study as the threshold to define high peak exposure.) The observed fraction of exposed subjects increased from 0.48 for two categories to 0.80 for five categories. Most subjects spent time in four or five activity categories during a day.

As an example of accumulation of exposed subjects by activity, consider the simple activity-related exposure model applied to the three-category group Home + In-bed + Travel. In the Kaiser SAB Study, 99.8% of subjects spent time in Home: 34% of these subjects had measurements above 16 mG and 66% did not. Of course, only the latter with maximum less then 16 mG could have their exposure increased by going to the In-bed category.

In the In-bed category, 4% of subjects had a maximum greater then 16 mG. Thus, the estimated fraction of subjects from the Home category who went from unexposed to exposed during time in the In-bed category is given by 0.66 times 0.04 or approximately 0.03 (3%) of all subjects. This 3% increment when added to the 34% exposed from the Home category yields 37% as the estimated percentage of exposed subjects from the Home and In-bed categories. The remaining 63% of unexposed subjects is susceptible to having their status elevated to exposed in Travel, where 39% of the subjects had a maximum greater than 16 mG. Thus, the estimated fraction of subjects in this group who went from unexposed to exposed during their time in the Travel category is given by 0.63 times 0.39 or approximately 0.25 (25%) of all subjects. This 25% increment added to the previously exposed 37% yields a total of 62% expected exposure rate for the three-activity group Home + In-bed + Travel. The actual observed rate of exposure for this group of 41 subjects was 76%.

Similar estimates of the fraction exposed were modeled for all the observed groups with 2, 3, 4, or 5 categories. The aggregated exposure fractions by number of activities are given in Table 4. The aggregated fractions by number of activities and across the entire study population are consistent with the observed results for increasing exposure with the number of activities.

Temporal Stability of Peak-Exposure Measures

Relationships between the first-visit and subsequent-visits peak-exposure measures were examined to determine the stability of these measures in the home over time in the EPRI LTWC Study. The mean time between the first and last visit to a house was 541 days, with a minimum of 60 days and a maximum of 623 days. The Spearman rank order correlation coefficient for the PE maximum was 0.31 between the first and last visit. As expected, correlation improved by moving from the maximum to the 99th and 95th percentiles. Spearman correlation coefficients for the latter two were 0.63 and 0.78, respectively.

Spearman rank order correlation coefficients between pairs of visits *versus* the time between visits are shown for selected PE peak-exposure measures and measures of central tendency in Figure 4. The correlation of maxima between visits ranged from 0.35 for visits separated by less than six months to 0.27 for visits separated by more than 15 months. The correlation coefficient ranged between 0.65 and 0.62 for the 99th percentile, and between 0.84 and 0.75 for the 95th percentile. For the median, the correlation coefficients ranged from 0.87 to 0.80. For the TWA the correlation coefficients ranged from 0.82 to 0.70.

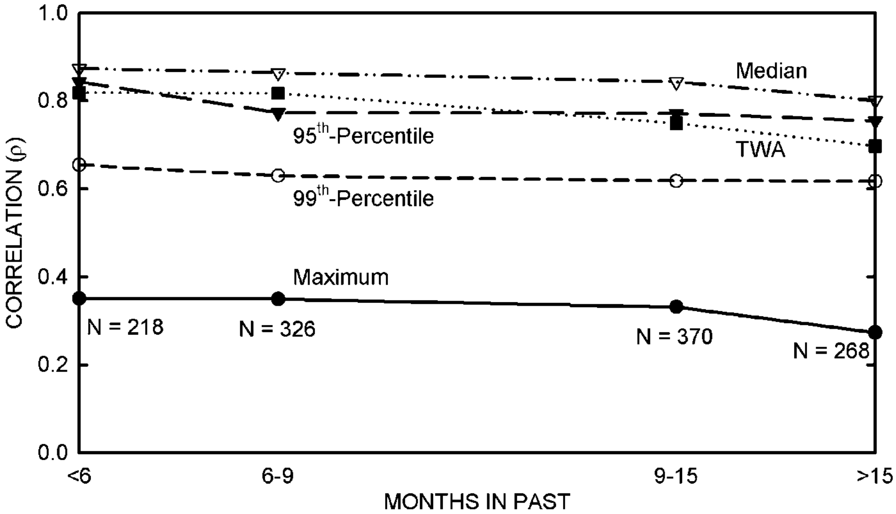

Figure 4. Spearman rank-order correlation coefficient between all visit pairs of peak-exposure measures and measures of central tendency in home by visit interval for the LTWC Study

Discussion

In EMF health studies, epidemiologists have traditionally relied on measures of central tendency, such as TWA, rather than measures of peak exposure. A main reason for not commonly using maxima and other peak measures is their presumed instability and, in the case of the maximum, high dependence on a single measurement out of thousands over a long measurement period. On the other hand, TWA represents the tendency for a relatively high or low exposure level over a protracted period. The two California studies reporting association between maximum magnetic fields and miscarriage (Lee et al., 2002; Li et al., 2002) however, attracted renewed interest in peak-exposure measures. Our analyses were mostly aimed at examining the stability of peak-exposure measures and at evaluating whether the maximum magnetic-field exposure is a function of activity as Savitz (2002) suggested.

Our analyses for discrete-interval sampling instruments showed that the value of the maximum magnetic-field exposure varied inversely with the sampling interval between magnetic-field measurements. Thus, the observed maximum for a subject and the mean and percentiles of maxima for a group of subjects depend on the sampling interval. For example, the 25th percentile for the daily maximum in the Kaiser study was 16 mG for a 10-s sampling interval. By extrapolation, we estimate that a 25th-percentile threshold for exposure would have been 21 mG had the investigators used a 4-s sampling interval for measurements. Thus, one should not attach biological significance to a particular threshold as an effect/no effect dividing line. No dependence on sampling interval was observed for the 99th-percentile summary measure for magnetic-field exposures, indicating its better stability as an indicator of peak exposure compared to the maximum.

Differences in the distributions of maxima and 99th percentiles were consistent across studies with the effects of sampling interval on the two measures: increased maxima with shorter intervals and no change in 99th-percentile values with sampling interval.

A probabilistic model for the fraction of subjects with maximum exposures above a specified threshold was developed. The model is based on the assumption that the distributions of exposures >16 mG in each category is independent and that the occurrence of exposures >16 mG within a category is independent of time spent in the category. This model demonstrates how the fraction of subjects above an exposure threshold is a function of the number of activity categories the subjects enter. For example, if all subjects stayed at home (Home and In-bed categories) in the Kaiser SAB Study, then about 37% of subjects would have had exposures with maximum above 16 mG. However, when subjects spent time in different activity categories, the percentage of subjects with maximum above 16 mG increased to 75%. Thus, this particular measure of peak exposure tends to classify active people into the higher exposure category.

These findings are consistent with the hypothesis put forth by Savitz (2002), who suggested that the associations between maximum magnetic fields and miscarriage in the California studies may plausibly result from behavioral differences between women with healthy pregnancies and women with miscarriage. It is important to note, however, that our results do not necessarily exclude the possibility of a relationship between peak exposure and miscarriage. Our results provide only indirect evidence that activity may play a role in the association between peak exposure and miscarriage. More direct evidence may only be provided by a follow-up epidemiologic study of miscarriage among pregnant women with simultaneous monitoring of magnetic field and activity levels.

As indicated by the Spearman correlation coefficients for repeated PE measurements in the same house, measures of central tendency tended to be more stable measures of exposure over time than were measures of peak exposure. The correlation was highest for the median (∼0.85) and lowest for the maximum (∼0.30). When more diverse environments outside the home are added to a subject's activities, we would expect the maximum to be even less stable over time. The correlation for the 99^{th}-percentile summary measure over time was ∼0.64, indicating considerably more stability than the maximum.

Any generalization from a given study to more global exposure characterization and risk assessment should be made with caution. The results presented here indicate that this is particularly the case with respect to the maximum and exposure measures derived from it, such as the presence of exposure above a threshold. The validity and robustness of these measures are compromised by their dependence on measurement protocols and subject activities. Future epidemiologic studies examining a potential association between peak magnetic field exposure measures and the risk of SAB should carefully evaluate the potential confounding effect of the women's activity level during pregnancy.

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