PERSONAL POWER-FREQUENCY MAGNETIC FIELD EXPOSURE IN WOMEN RECRUITED AT AN INFERTILITY CLINIC: ASSOCIATION WITH PHYSICAL ACTIVITY AND TEMPORAL VARIABILITY

Ryan C. Lewis¹, Russ Hauser^{2,3}, Lu Wang⁴, Robert Kavet⁵ and John D. Meeker^{1,*}

¹Department of Environmental Health Sciences, University of Michigan School of Public Health, 1835 SPH I, 1415 Washington Heights, Ann Arbor, MI 48109, USA

²Department of Environmental Health, Harvard School of Public Health, Building I, 14th Floor, 665 Huntington Avenue, Boston, MA 02115, USA

³Vincent Memorial Obstetrics and Gynecology Service, Massachusetts General Hospital, 55 Fruit Street, Boston, MA 02114, USA

⁴Department of Biostatistics, University of Michigan School of Public Health, M4132 SPH II, 1415 Washington Heights, Ann Arbor, MI 48109, USA

⁵Electric Power Research Institute, 3420 Hillview Avenue, Palo Alto, CA 94304, USA

*Corresponding author: meekerj@umich.edu

Received 13 February 2015; revised 11 June 2015; accepted 13 June 2015

Current epidemiologic approaches for studying exposure to power-frequency magnetic fields and the risk of miscarriage are potentially biased due to lack of attention to the relationship of exposure with physical activity and within-individual variability in exposures over time. This analysis examines these two issues using data from a longitudinal pilot study of 40 women recruited from an infertility clinic that contributed data for up to three 24-h periods separated by a median of 3.6 weeks. Physical activity was positively associated with peak exposure metrics. Higher physical activity within environments did not necessarily lead to higher peak exposures, suggesting that movement between and not within environments increases one's probability of encountering a high field source. Peak compared with central tendency metrics were more variable over time. Future epidemiology studies associated with peak exposure metrics should adjust for physical activity and collect more than 1 d of exposure measurement to reduce bias.

INTRODUCTION

Prior to 2002, the consensus of expert opinion was that the evidence potentially linking exposure to power-frequency (i.e. 50 or 60 Hz depending on the country) magnetic fields and adverse reproductive health outcomes was deemed inadequate^(1–3). However, the concern was revived following the publication of two epidemiology studies conducted among women from the Northern California Kaiser Permanente hospital system^(4, 5). These two studies reported that a woman's daily maximum personal magnetic field exposure, but not time-weighted average (TWA) exposure, was positively associated with her risk of miscarriage. Associations were stronger in those with a history of subfertility and/or multiple miscarriages, which, as the authors hypothesised, may represent 'susceptible' sub-populations. Following the publication of these studies, the California Department of Health Services released a report stating that a 'substantial proportion of miscarriages' might be caused by exposure to magnetic fields and that, if true, this would be cause for 'personal and regulatory concern'⁽⁶⁾. However, there were a number of limitations associated with these epidemiology studies

that tempered their results, primarily confounding due to unmeasured physical activity and the timing and frequency of exposure measures used in the analysis.

An accompanying commentary proposed that the basis for the miscarriage association with the maximum personal magnetic field exposure could be rooted in different mobility patterns in women with healthy pregnancies compared with women who miscarried⁽⁷⁾. In early pregnancy (first trimester), women with morning sickness, an indicator of a healthy pregnancy, would be less physically active compared with women with less healthy pregnancies and more likely to have a miscarriage. In late pregnancy, women close to term would have more discomfort and difficulty moving from place to place compared with women who had experienced miscarriage. Savitz⁽⁷⁾ suggested that a decreased mobility in healthy pregnancies would translate to a decreased probability of encountering sources of high magnetic fields, and, as a result, lower maximum magnetic field exposures. On the other hand, increased mobility in women who miscarried would result in greater maximum magnetic field exposures, but not due to a causal relationship between magnetic fields and miscarriage.

Findings from a small number of exposure assessment studies support Savitz's hypothesis, with results suggesting a positive association of physical activity with maximum personal magnetic field exposure^(8, 9). However, these studies were limited in number and scope. Studies are also needed on the distribution and temporal variability of daily personal magnetic field exposure metrics among women, especially as they relate to durations that are relevant to pregnancy time windows (i.e. sampling days separated by weeks or months), as they are likewise relevant to reducing bias resulting from magnetic field exposure characterisation in miscarriage epidemiology studies.

The primary aim of the present analysis was to assess the association between physical activity and daily personal magnetic field exposures in women. What has been published previously is extended by modelling physical activity using accelerometer data and time-activity diary data to quantify frequency of movement between environments in relation to six central tendency and peak daily personal magnetic field exposure metrics. The secondary aims of the study were to assess the long-term (over several weeks) temporal variability of daily personal magnetic field exposure metrics in women and to characterise magnetic field exposures in a sub-fertile population. This analysis builds on the authors' previous work where they examined the short-term (over one week) temporal variability of daily magnetic field exposure metrics in pregnant women from a separate cohort⁽²⁾; the association between physical activity and magnetic field exposure and the long-term temporal variability of daily magnetic field exposure metrics were not explored in that study. The results of the current analysis are expected to inform the design of future epidemiology studies, which in turn will lead to more valid effect estimates and refine the understanding of the potential relationship between magnetic fields and miscarriage.

MATERIALS AND METHODS

Study participants

Women ($n = 40$) in this study were enrolled in the Environment and Reproductive Health (EARTH) study, which is an ongoing collaboration between the Massachusetts General Hospital (MGH) Fertility Center and the Harvard School of Public Health (HSPH) studying how the environment influences infertility^(10, 11). Female participants were partners in couples seeking infertility treatment at MGH due to a female factor, a male factor or a combination of both female and male factors.

First, women were recruited into the EARTH study by a trained research nurse at MGH. Women agreeing to participate in the EARTH study were then also recruited into a pilot study to determine the feasibility

of recruiting subjects to wear a personal magnetic field exposure monitor and an accelerometer and to record their activities in a diary every 30 min for three 24-h periods. In other words, the pilot study was nested within the larger EARTH study.

The research protocol was approved by the Institutional Review Boards of MGH, HSPH, the Centers for Disease Control and Prevention, and the University of Michigan. Those women agreeing to participate in the study signed an informed consent after the study procedures were explained to them, and their questions were answered by a trained research nurse.

Time-activity diary

Participants were asked to complete a time-activity diary (see Supplemental File), which was modelled after the one used in the U.S. National Children's Study (<http://www.nationalchildrensstudy.gov>) and consisted of describing their daily activities and locations at 30-min intervals.

Measurement of magnetic field exposure and physical activity

Participants were asked to wear at the hip level a small personal magnetic field exposure monitor (EMDEX LITE, Enertech, Campbell, CA, USA). The EMDEX LITE was calibrated to measure the magnetic field level in milliGauss ($1 \text{ mG} = 0.1 \mu\text{T}$) every 4 s at 60 Hz with a frequency band ranging from 40 to 1000 Hz. The resultant magnetic field level of the X, Y and Z planes was used in the present analysis.

Participants were also asked to wear at the hip level an ActiGraph accelerometer (Model Number GT3X, Pensacola, FL, USA). The ActiGraph is a tri-axial accelerometer that reports movement as 'counts per epoch' (average counts every 2 s for this study) from the measured accelerations (g) in the X, Y and Z planes. Similar to the EMDEX LITE, physical activity level was defined as the resultant average counts across these three axes. Average counts represented an indication of total movement, with higher counts representing higher overall physical activity.

Women were instructed to wear both the monitors throughout the entire monitoring period (i.e. inside and outside the home), except at bedtime and when bathing, showering or swimming. These monitors, as well as similar monitors, have been used in numerous other studies conducted in adults^(2, 4, 5, 8, 12-17).

Although the ActiGraph provides an objective measure of overall physical activity, it does not necessarily characterise movement between environments, which may be a more relevant metric in understanding the potential relationship between physical activity and personal magnetic field exposure as hypothesised by Savitz⁽⁷⁾. To address this limitation of the ActiGraph, the time-activity diary was used to quantify the daily

total number of changes in environments experienced per 24-h period.

Measurement of other variables

A research nurse administered a questionnaire to collect data on age, race/ethnicity, height, weight and occupation at enrolment. Participants completed a follow-up questionnaire online where information on education was collected.

Statistical analysis

Statistical analyses were performed using SAS version 9.3 for Windows (SAS Institute, Cary, NC, USA).

Prior to conducting any statistical analyses, non-wear time data as reported in their time-activity diaries was removed from each data set^(2, 9, 14, 18). Descriptive statistics of the cohort were calculated for the following variables: age, race/ethnicity, body mass index [BMI, weight (kg) ÷ height (m²)], occupation and education. For each participant, daily central tendency (TWA, median) and peak (90th, 95th and 99th percentiles, maximum) personal magnetic field exposure metrics, monitor wear durations, average activity counts and the total number of changes in environments experienced were calculated. Distributions of magnetic field exposure metrics and average counts were estimated for the entire sampling day and by environment because it was hypothesised that magnetic field exposure and physical activity profiles may differ between settings.

To assess between- and within-person variability in daily personal magnetic field exposure metrics over the course of repeated sampling days, which were typically separated by several weeks, intraclass correlation coefficients (ICCs) were calculated using variance components from linear mixed models with only one random effect as the random intercept for each subject. ICCs were also calculated for average counts and the total number of changes in environments experienced. The magnitudes of the ICCs were evaluated using the following criteria: poor reproducibility ($ICC < 0.40$), fair to good reproducibility ($0.40 \leq ICC < 0.75$) and excellent reproducibility ($ICC \geq 0.75$)⁽¹⁹⁾. ICCs were calculated using available data from women that contributed 2–3 sampling days.

While the ICC is an indicator of the temporal reliability for continuous measures, it does not quantify the magnitude of exposure misclassification if participants are categorised into different exposure groups (e.g. low vs. high exposure). When treating the exposure data as categorical variables, sensitivity and specificity of a single-day personal magnetic field exposure metric (i.e. 'surrogate' or 'predicted') as a predictor of a high or low long-term personal magnetic field exposure metric (i.e. 'observed', all sampling days for each participant over several weeks) were evaluated by comparing

the surrogate and observed exposure levels for agreement. For each woman, each daily exposure metric served as a surrogate for the long-term exposure metric and was included in the long-term exposure metric calculation, which was derived using the data across all sampling days. This process was repeated for each sampling day for each participant, resulting in three separate 2×2 contingency tables (i.e. one for each sampling day). All three tables were then combined into a single table, where overall sensitivity and specificity were calculated. Sensitivity and specificity were calculated for the personal magnetic field exposure metrics assessed in the ICC analysis for thresholds corresponding to the 50th, 75th and 90th percentiles of the daily exposure metrics. Sensitivity and specificity were calculated using available data from women that contributed 2–3 sampling days.

Physical activity (predictor variable) was modelled in this analysis as both daily average counts and the total number of changes in environments experienced, and their respective associations with daily central tendency and peak personal magnetic field exposure metrics (outcome variable) were assessed in linear mixed models with only one random effect as the random intercept for each subject to account for the correlation of magnetic field exposure measurements within an individual. Physical activity was separately modelled as both continuous (to explore potential linear relationships) and categorical (to explore potential non-linear relationships) variables, resulting in four linear mixed models: (i) average counts, (ii) tertiles of average counts, (iii) the total number of changes in environments experienced and (iv) categories of the total number of changes in environments experienced. The *p*-values associated with the trend lines for these models were also calculated. Statistical significance was defined as a $p \leq 0.05$.

RESULTS

Forty women were recruited into the pilot study. These women had a mean age of 34.6 y and a mean BMI of 23.8 kg m⁻², and were predominantly Caucasian (70.0 %), highly educated (58.3 % with graduate degrees) and working professionals (90.0 %). The monitors were worn for a median of 15.0 h d⁻¹ [interquartile range (IQR): 14.0, 16.0 h] during separate sampling days that were separated by a median of 3.6 weeks (IQR: 2.9, 5.1 weeks) within the participants. While it was expected that data from 120 separate sampling days would have been collected during the pilot study, at most 89 sampling days were incorporated into the present analysis due to missing data.

Table 1 shows the distribution of the daily personal magnetic field exposure metrics for the entire cohort. The geometric mean (GM) daily personal magnetic field exposure level was 1.2 mG for the TWA and 34.4 mG for the maximum. When stratifying on environment,

Table 1. Distribution of daily personal magnetic field exposure metrics (mG) and daily magnetic field exposure monitor and accelerometer wear time (hours) by environment.

Environment	Daily wear time Median (IQR)	Metric	GM	Percentiles		
				25th	50th	75th
Total ^a	15.0 (14.0, 16.0)	TWA	1.2	0.8	1.1	1.7
		Maximum	34.4	20.0	36.0	55.0
Inside at home ^a	8.0 (4.5, 11.0)	TWA	1.0	0.6	1.0	1.6
		Maximum	14.9	10.4	15.0	25.8
Inside at work or school ^b	7.5 (6.5, 8.5)	TWA	0.9	0.4	0.7	1.8
		Maximum	20.0	10.2	18.9	31.2
Inside somewhere else ^c	2.0 (1.0, 3.5)	TWA	1.2	0.8	1.2	2.0
		Maximum	16.3	10.8	18.0	32.8
Outside at home ^d	0.5 (0.5, 1.5)	TWA	1.1	0.8	1.0	1.7
		Maximum	7.3	4.1	6.5	12.5
Outside at work or school ^e	1.0 (0.5, 1.5)	TWA	1.0	0.6	1.0	1.2
		Maximum	15.1	8.0	11.2	28.9
Outside somewhere else ^f	1.5 (1.0, 2.5)	TWA	1.7	1.0	1.8	2.7
		Maximum	20.6	11.6	23.6	38.5
In transit ^g	1.5 (1.0, 2.5)	TWA	1.8	1.3	1.7	2.5
		Maximum	24.5	13.7	23.7	41.4

GM, geometric mean; IQR, interquartile range; max., maximum; TWA, time-weighted average.

^a89 sampling days from 40 women.

^b45 sampling days from 23 women.

^c57 sampling days from 31 women.

^d22 sampling days from 16 women.

^e14 sampling days from 11 women.

^f58 sampling days from 29 women.

^g72 sampling days from 32 women.

TWAs were relatively similar (GM range: 0.9–1.8 mG), whereas maximums varied widely, with the highest and lowest maximums experienced on average were in transit (GM: 24.5 mG) and outside at the home (GM: 7.3 mG), respectively. Most time over the course of the day was spent inside at home, followed by inside at work or school, inside somewhere else, outside somewhere else, in transit, outside at work or school and outside at home. On average, women tended to be most active while outside somewhere else, followed by outside at home, outside at work or school, in transit, inside somewhere else, inside at home and inside at work or school (data not shown). Using physical activity inside at home as a reference, women were approximately 3.42, 3.08, 2.65, 1.93, 1.79 and 0.91 times as active outside somewhere else, outside at home, outside at work or school, in transit, inside somewhere else and inside at work or school, respectively.

ICCs, presented in Table 2, varied widely between daily central tendency and peak personal magnetic field exposure metrics. The TWA (ICC: 0.63), median (ICC: 0.56), 90th percentile (ICC: 0.62) and 95th percentile (ICC: 0.59) were the most stable, exhibiting fair to good reproducibility, followed by the 99th percentile (ICC: 0.32) and the maximum (ICC: 0.13), which both showed poor reproducibility. These relationships

were also qualitatively observable in Figure 1, where the temporal variability in the daily personal magnetic exposure metrics is plotted for 10 randomly selected participants. In particular, the peak magnetic field exposure metrics towards the upper tail of the distribution (i.e. 99th percentile, maximum) demonstrated greater intra-individual variability than the other personal magnetic field exposure metrics for these women. In addition, there was poor reproducibility for both daily average activity counts (ICC: 0.39) and the daily total number of environments experienced (ICC: 0.37).

In the present assessment of sensitivity, the proportion of participants who had an elevated long-term personal magnetic field exposure (i.e. all sampling days for each participant over several weeks) and would be classified as such using a single-day personal magnetic field exposure metric (i.e. sensitivity) ranged from 0.67 (threshold: ≥ 2.7 mG) to 0.81 (threshold: ≥ 1.2 mG) for the TWA, 0.67 (threshold: ≥ 2.1 mG) to 0.83 (threshold: ≥ 0.7 mG) for the median, 0.67 (threshold: ≥ 4.7 mG) to 0.78 (threshold: ≥ 2.1 mG) for the 90th percentile, 0.50 (threshold: ≥ 5.8 mG) to 0.72 (threshold: ≥ 3.1 mG) for the 95th percentile, 0.50 (threshold: ≥ 13.7 mG) to 0.73 (threshold: ≥ 6.9 mG) for the 99th percentile and 0.39 (threshold: 85.4 mG) to 0.59 (threshold: 34.9 mG) for

the maximum. The sensitivities decreased with increasing exposure thresholds. In the assessment of specificity, the proportion of women with a long-term personal

Table 2. Between- and within-subject variance apportionments and ICCs for log-transformed daily personal magnetic field exposure metrics separated by several weeks.

Metric	Variance estimate ^a		ICC
	Between subject	Within subject	
TWA	0.25	0.15	0.63
Median	0.31	0.24	0.56
90th percentile	0.29	0.18	0.62
95th percentile	0.24	0.17	0.59
99th percentile	0.15	0.32	0.32
Maximum	0.09	0.59	0.13

ICC, intraclass correlation coefficient; TWA, time-weighted average.

^aDerived from linear mixed models with only one random effect as the random intercept for each subject using 74 sampling days from 27 women.

magnetic field exposure that was not elevated and would be classified as such using a single-day personal magnetic field exposure metric (i.e. specificity) ranged from about 0.91 to 0.94 for the TWA, 0.85 to 0.93 for the median, 0.96 to 0.98 for the 90th percentile, 0.86 to 0.97 for the 95th percentile and 0.76 to 0.97 for the 99th percentile; specificity was 1.00 for all exposure thresholds associated with the maximum. The specificities were generally similar across the exposure thresholds, and the magnitude of the specificities was greater than their respective sensitivities.

Figure 2 is illustrative and shows the personal magnetic field exposure data across two 24-h sampling periods for two separate women with low and high average counts, respectively. Qualitatively there appears to be a positive association between physical activity and personal magnetic field exposure level, where the probability of experiencing an elevated magnetic field exposure was greater in more active compared with less active women.

Table 3 shows the associations between physical activity, modelled as both daily average counts and the daily total number of changes in environments experienced, and daily personal magnetic field exposure

Figure 1. Variation in daily personal magnetic field exposure metrics separated by several weeks for a randomly selected subset of the same 10 participants.

POWER-FREQUENCY MAGNETIC FIELD EXPOSURE IN WOMEN

Figure 2. Personal magnetic field exposure over a 24-h sampling period for two representative data sets from two participants with low and high average counts, respectively, relative to the entire data set.

Table 3. Association between daily average counts and the daily total number of changes in environments experienced (IQR increase for both variables) and log-transformed daily personal magnetic field exposure metrics (mG).

Metric	Average counts			Total number of changes in environments experienced		
	$\beta^{a,b}$	95 % CI	<i>p</i> -Value	$\beta^{a,c}$	95 % CI	<i>p</i> -Value
TWA	0.07	−0.14, 0.29	0.48	0.12	−0.06, 0.24	0.13
Median	0.13	−0.14, 0.43	0.35	0.06	−0.12, 0.24	0.71
90th percentile	0.07	−0.14, 0.29	0.55	0.18	0.02, 0.36	0.02
95th percentile	0.14	−0.09, 0.43	0.20	0.24	0.12, 0.42	0.0006
99th percentile	0.43	0.10, 0.58	0.007	0.30	0.12, 0.54	0.0008
Maximum	0.43	0.13, 0.72	0.007	0.24	−0.001, 0.48	0.05

CI, confidence interval; TWA, time-weighted average.

^aEach β estimate is from a separate model.

^bDerived from linear mixed models with only one random effect as the random intercept for each subject and a fixed effect for daily average counts using 77 sampling days from 38 women.

^cDerived from linear mixed models with only one random effect as the random intercept for each subject and a fixed effect for the daily total number of changes in environments experienced using 89 sampling days from 40 women.

metrics. There were statistically significant positive associations between average counts and the 99th percentile and the maximum magnetic field exposure and

between the total number of changes in environments experienced and the 90th, 95th and 99th percentiles and the maximum magnetic field exposure.

As shown in Figures 3 and 4, when physical activity was modelled as a categorical variable, there was a statistically significant positive association between tertiles of average counts and the 99th percentile and the maximum magnetic field exposure, whereas there was a statistically significant positive association between categories of the total number of changes in environments experienced and the 95th and 99th percentiles and the maximum magnetic field exposure. The regression coefficients and corresponding 95 % confidence intervals (CIs) for the 'medium' and 'high' groups, respectively, in Figure 3 are as follows: TWA, 0.01 (−0.27, 0.30) and 0.02 (−0.30, 0.35); median, 0.21 (−0.14, 0.56) and 0.22 (−0.18, 0.61); 90th percentile, 0.14 (−0.18, 0.46) and 0.08 (−0.29, 0.45); 95th percentile, 0.14 (−0.17, 0.44) and 0.15 (−0.19, 0.50); 99th percentile, 0.08 (−0.36, 0.51) and 0.35 (−0.11, 0.80); and maximum, 0.09 (−0.46, 0.64) and 0.54 (−0.00, 0.64). Similarly, the regression coefficients and corresponding 95 % CIs for the '6–9' and '≥10' groups, respectively, in Figure 4 are as follows:

TWA, −0.14 (−0.49, 0.20) and 0.04 (−0.32, 0.41); median, −0.09 (−0.53, 0.34) and −0.02 (−0.48, 0.44); 90th percentile, −0.16 (−0.53, 0.22) and 0.11 (−0.29, 0.51); 95th percentile, 0.01 (−0.34, 0.37) and 0.35 (−0.03, 0.73); 99th percentile, 0.33 (−0.09, 0.76) and 0.70 (0.26, 1.14); and maximum, 0.63 (0.11, 1.15) and 0.74 (0.21, 1.27).

DISCUSSION

In this pilot study, the association between physical activity and daily personal magnetic field exposure and the temporal variability of daily personal magnetic field exposure metrics separated by several weeks were evaluated in a cohort of 40 women seeking infertility treatment at MGH. Physical activity, when modelled as daily average counts and the daily total number of changes in environments experienced, was positively associated with peak personal magnetic field exposure metrics, especially the upper percentiles and the maximum, but not with central

Figure 3. Change in log-transformed daily personal magnetic field exposure metrics associated with tertiles of daily average counts. Derived from linear mixed models with one random effect as the random intercept for each subject and fixed effects for tertiles of daily average counts. Low = 26 sampling days from 19 women, medium = 25 sampling days from 20 women and high = 26 sampling days from 19 women.

POWER-FREQUENCY MAGNETIC FIELD EXPOSURE IN WOMEN

Figure 4. Change in log-transformed daily personal magnetic field exposure metrics associated with the daily total number of changes in environments experienced. Derived from linear mixed models with one random effect as the random intercept for each subject and fixed effects for categories of the daily total number of changes in environments experienced. Less than 6 changes = 21 sampling days from 14 women, 6–9 changes = 34 sampling days from 23 women and ≥ 10 changes = 34 sampling days from 21 women.

tendency metrics. There were also differences in personal magnetic field exposures and physical activity by environment. Single-day continuous and categorical central tendency metrics of personal magnetic field exposure were more stable over time compared with peak metrics, especially the 99th percentile and the maximum.

To the authors' knowledge, no previous studies have characterised personal magnetic field exposures in sub-fertile populations, which are hypothesised by some to be more susceptible to adverse reproductive health effects potentially associated with exposures to environmental agents, such as magnetic fields⁽⁵⁾. Differences in personal magnetic field exposures by environment were observed, which have been reported by others⁽²⁰⁾. These results suggest that environment may be an important determinant in the interaction of women with magnetic field sources. For example, the opportunity for elevated magnetic field exposures was the greatest while in transit, which may be due to

elevated exposures resulting from the use of alternating current-powered railways and/or travel near power transmission lines and other high magnetic field sources that dominate urban settings. As expected, participants tended to be more physically active outdoors relative to indoors. However, higher physical activity within the environments examined did not necessarily lead to higher maximum personal magnetic field exposures (i.e. the rank order of physical activity by environment did not match with that of maximum magnetic field exposure by environment), suggesting that movement between environments and not within the same environment increases one's probability for encountering a high field source.

Comparing the present data with those measured over a single 24-h period in a representative subset of US women and men ≥ 18 to < 65 y old ($n = 716$) in 1996–97 (the 1000-Person Survey)⁽²⁰⁾, the GM TWA in the present analysis was slightly higher with a value of 1.2 versus 1.0 mG for the US survey. This difference in

the measured exposures might be due to differences in sampling mechanics of the meters. The EMDEX LITE, which was used in this study, had a 4-s sampling frequency, whereas the EMDEX PAL used in the 1000-Person Survey sampled at 0.5-s intervals and accumulated data for 10 min prior to calculating summary measures. In addition, this study had a slightly higher GM TWA (1.2 vs. 0.8 mG) and a much higher GM maximum (34.4 vs. 10.4 mG) in comparison with a recent study of personal magnetic field exposures measured over 7 consecutive days in a cohort of pregnant women from North Carolina ($n = 100$)⁽²⁾. Compared with the supplemental analyses of the single 24-h personal magnetic field exposure levels measured in the California Kaiser Spontaneous Abortion Study ($n = 960$)^(5, 21), the GM TWA (1.2 vs. 1.2 mG) in the present study was similar, but the GM maximum (34.4 vs. 29.9 mG) was slightly higher in this study. The large differences, apparent in the maximums between the present study (sampling interval: 4 s), the North Carolina study (sampling interval: 60 s) and the Kaiser Study (sampling interval: 10 s), may be due to differences in sampling frequency as well. In particular, Mezei *et al.*⁽⁸⁾ showed that less frequent sampling underestimates the daily maximum, which may explain why the maximums in the present analysis were considerably higher than those in studies with lower sampling rates.

The authors are aware of only a few peer-reviewed studies that have assessed intra-individual temporal variability among adult personal magnetic field exposure metrics that integrate exposures from magnetic field sources inside and outside the home, including the workplace. A recent analysis of the personal magnetic field exposures measured over 7 consecutive days in pregnant women from North Carolina demonstrated that the median (ICC: 0.66) was the most stable over the short term (i.e. day-to-day variability), followed by the TWA (ICC: 0.64), 90th percentile (ICC: 0.55), 95th percentile (ICC: 0.49), 99th percentile (0.43) and maximum (ICC: 0.37)⁽²⁾. The magnitude of the ICCs in the North Carolina cohort was largely in the same range that was observed in the present analysis (i.e. approximately month-to-month variability), except that the maximum reported in this study was much less stable (ICC: 0.13). Differences in the ICCs between the two studies may be a result of the different sampling frequencies of the magnetic field exposure monitors as described previously and/or differences in mobility patterns over time, resulting in more or less variable interactions with magnetic field sources. Similar to Lewis *et al.*⁽²⁾, it was also observed in this study that for categorical exposure metrics temporal variability appears to be dictated by the selected threshold, with decreasing stability over time with increasing threshold. However, it is possible that the calculated sensitivities and specificities might be slightly overestimated because the predicted values were included in the calculation of the observed values, and, as a result, the predicted and

observed values were not independent⁽²²⁾. Nevertheless, the present study and the North Carolina study suggest that peak personal magnetic field exposure metrics tend to be less stable over time compared with central tendency metrics. If there is interest in characterising personal magnetic field exposures in epidemiology studies with either short (e.g. unsuccessful fertilisation, implantation failure) or longer latency windows (e.g. miscarriage) and the maximum or other upper percentiles are the metric of interest, then collecting more than 1 d of sampling is necessary to reduce measurement error. Other studies have also examined the temporal variability of continuous and categorical personal magnetic field exposure metrics in women and have reported similar findings^(4, 8).

To date, only one peer-reviewed study has examined the association between physical activity level using accelerometer data and personal magnetic field exposure metrics in women. In that study, Savitz *et al.*⁽⁹⁾ reported that average counts were positively associated with the maximum, but not with the TWA, in a cohort of pregnant women from North Carolina. Similar findings were observed for the maximum and the TWA in this analysis, as well as associations with upper percentiles, but not the median. Not only more daily personal magnetic field exposure metrics were examined in the present study than the Savitz *et al.*⁽⁹⁾ study, but the association between frequency of moving between environments, which may be a more valid metric of physical activity in this context, and personal magnetic field exposure was also explored. Similar to the accelerometer data, positive associations were found between the total number of changes in environments experienced and peak personal magnetic field exposure metrics, but not central tendency metrics. Mezei *et al.*⁽⁸⁾ have also reported that the daily number of activities (e.g. home + work + travel + other) in women from the Kaiser study was positively associated with the maximum personal magnetic field exposures. Taken together, the present analysis, along with those published previously, suggests that effect estimates for epidemiology studies of peak personal magnetic field exposure metrics and miscarriage may be biased. Unmeasured confounding may be present, if physical activity was not included in statistical models as was the case for the studies published by Lee *et al.*⁽⁴⁾ and Li *et al.*⁽⁵⁾ that reported an increase in risk of miscarriage from elevated personal magnetic field maximum exposures. Both daily accelerometer data and daily frequency of moving between environments are potentially valid methods for quantifying physical activity in this context. However, as with measures of peak magnetic field exposure, more than 1 sampling day of physical activity will be necessary to reduce measurement error.

Unique strengths of this study included the robustness of the data set, which included thousands of data points per day within each individual, the breadth of magnetic field exposure and physical activity metrics

examined, and the use of the time–activity diary, which allowed for exploring the relationship between the environment and magnetic field exposure and physical activity. One limitation of this study was the small sample size, which may have limited the statistical power of the analyses. Several approaches were also used to explore several magnetic field exposure science issues, and, as a result, some of the findings may be due to multiple testing. Nevertheless, the results of the present analysis demonstrated statistical significance and were largely consistent with the small number of studies that have examined temporal variability of personal magnetic field exposure metrics in adults and the association between physical activity level and personal magnetic field exposures in adults^(2, 4, 8, 9). It is also unlikely that the models of physical activity and personal magnetic field exposure could have been biased due to unmeasured confounding. There appear to be no plausible variables that could confound this relationship, and, similar to the present analysis, Savitz *et al.*⁽⁹⁾ did not adjust their models for any confounding factors for statistical reasons. In addition, while only 60 % of the women approached were recruited into the pilot study, selection bias is limited as they were similar to the women of the overall EARTH cohort on demographic factors. Selection bias due to missing data is also limited as the missing data were from women who had already contributed data to the available data set. Thus, the missing data should be comparable with the data used in the analysis assuming that there were no major variations in participant behaviour during these missing time periods.

CONCLUSIONS

In summary, a comprehensive, pilot analysis of the association between physical activity and personal magnetic field exposure and temporal variability of personal magnetic field exposure metrics was conducted over several weeks. It was showed in this study that physical activity is positively associated with peak personal magnetic field exposure and, assuming it is also associated with nausea in early pregnancy or size in later pregnancy (which are associated with healthy pregnancies), it should be adjusted for accordingly in statistical models of magnetic fields and miscarriage to reduce any bias due to confounding. In such studies, if there is interest in peak personal magnetic field exposure metrics (e.g. upper percentiles, maximum), more than 1 d of measurement is needed over the window of susceptibility to minimise measurement error, but 1 d may be sufficient to characterise central tendency personal magnetic field exposure metrics. However, the number of sampling days per participant is study specific and should be balanced by the realistic financial and participant burden constraints often associated with large-scale epidemiology studies.

SUPPLEMENTARY DATA

Supplementary data are available at *RADDOS* Journal online.

ACKNOWLEDGEMENTS

The authors thank Patricia Morey, Jennifer Ford and Myra Keller for their assistance in data collection and participant recruitment.

CONFLICT OF INTEREST

Robert Kavet is employed by the Electric Power Research Institute, which partially funded this research. All the other authors declare no conflict of interest.

FUNDING

Work was supported by the Electric Power Research Institute and grants R01 ES009718 and R01 ES016099 from the National Institute of Environmental Health Sciences of the National Institutes of Health.

REFERENCES

1. Ahlbom, I. C., Cardis, E., Green, A., Linet, M., Savitz, D. and Swerdlow, A. *Review of the epidemiologic literature on EMF and health*. Environ. Health Perspect. **109**, 911–933 (2001).
2. Lewis, R. C., Evenson, K. R., Savitz, D. A. and Meeker, J. D. *Temporal variability of daily personal magnetic field exposure metrics in pregnant women*. J. Expo. Sci. Environ. Epidemiol. **2**, 58–64 (2015).
3. National Institute of Environmental Health Sciences. *Assessment of Health Effects from Exposure to Power-Line Frequency Electric and Magnetic Fields*. NIH Publication No. 98–3981 (1998). http://www.niehs.nih.gov/health/assets/docs_a_e/emf1.pdf (9 November 2012, date last accessed).
4. Lee, G. M., Neutra, R. R., Hristova, L., Yost, M. and Hiatt, R. A. *A nested case-control study of residential and personal magnetic field measures and miscarriages*. Epidemiology **13**, 21–31 (2002).
5. Li, D. K., Odouli, R., Wi, S., Janevic, T., Golditch, I., Bracken, T. D., Senior, R., Rankin, R. and Iriye, R. *A population-based prospective cohort study of personal exposure to magnetic fields during pregnancy and the risk of miscarriage*. Epidemiology **13**, 9–20 (2002).
6. Neutra, R. R., DelPizzo, V. and Lee, G. M. *An Evaluation of the Possible Risks from Electric and Magnetic Fields (EMFs) from Power Lines, Internal Wiring, Electrical Occupations and Appliances* (2002). <http://www.ehib.org/emf/RiskEvaluation/riskeval.html> (9 November 2012, date last accessed).
7. Savitz, D. A. *Magnetic fields and miscarriage*. Epidemiology **13**, 1–4 (2002).
8. Mezei, G., Bracken, T. D., Senior, R. and Kavet, R. *Analyses of magnetic-field peak-exposure summary measures*. J. Expo. Sci. Environ. Epidemiol. **16**, 477–485 (2006).

9. Savitz, D. A., Herring, A. H., Mezei, G., Evenson, K. R., Terry, J. W. Jr. and Kavet, R. *Physical activity and magnetic field exposure in pregnancy*. Epidemiology **17**, 222–225 (2006).
10. Ehrlich, S., Williams, P. L., Missmer, S. A., Flaws, J. A., Berry, K. F., Calafat, A. M., Ye, X., Petrozza, J. C., Wright, D. and Hauser, R. *Urinary bisphenol A concentrations and implantation failure among women undergoing in vitro fertilization*. Environ. Health Perspect. **120**, 978–983 (2012).
11. Meeker, J. D., Calafat, A. M. and Hauser, R. *Urinary phthalate metabolites and their biotransformation products: predictors and temporal variability among men and women*. J. Expo. Sci. Environ. Epidemiol. **22**, 376–385 (2012).
12. Evenson, K. R., Wen, F., Hillier, A. and Cohen, D. A. *Assessing the contribution of parks to physical activity using global positioning system and accelerometry*. Med. Sci. Sports Exerc. **45**, 1981–1987 (2013).
13. Hawkins, M. S., Storti, K. L., Richardson, C. R., King, W. C., Strath, S. J., Holleman, R. G. and Kriska, A. M. *Objectively measured physical activity of USA adults by sex, age, and racial/ethnic groups: a cross-sectional study*. Int. J. Behav. Nutr. Phys. Act. **6**, 31 (2009).
14. Jilcott, S. B., Evenson, K. R., Laraia, B. A. and Ammerman, A. S. *Association between physical activity and proximity to physical activity resources among low-income, midlife women*. Prev. Chronic Dis. **4**, A04 (2007).
15. Li, D. K., Yan, B., Li, Z., Gao, E., Miao, M., Gong, D., Weng, X., Ferber, J. R. and Yuan, W. *Exposure to magnetic fields and the risk of poor sperm quality*. Reprod. Toxicol. **29**, 86–92 (2010).
16. Li, D. K., Chen, H. and Odouli, R. *Maternal exposure to magnetic fields during pregnancy in relation to the risk of asthma in offspring*. Arch. Pediatr. Adolesc. Med. **165**, 945–950 (2011).
17. Troiano, R. P., Berrigan, D., Dodd, K. W., Mâsse, L. C., Tilert, T. and McDowell, M. *Physical activity in the United States measured by accelerometer*. Med. Sci. Sports Exerc. **40**, 181–188 (2008).
18. Buchowski, M. S., Choi, L., Majchrzak, K. M., Acra, S., Mathews, C. E. and Chen, K. Y. *Seasonal changes in amount and patterns of physical activity in women*. J. Phys. Act. Health. **6**, 252–261 (2009).
19. Rosner, B. *Multisample inference*. In: Fundamentals of Biostatistics, 5th edn. Cengage Learning (2000) ISBN 0534370683.
20. Zaffanella, L. E. and Kalton, G. W. *Survey of Personal Magnetic Field Exposure, Phase II: 1000-Person Survey* (1998). <http://www.emf-data.org/rapid6-report.html> (10 October 2013, date last accessed).
21. Bracken, T. D. *Supplemental Analyses of Magnetic Field Personal Exposure Data from the Kaiser Spontaneous Abortion Study* (2002). <http://www.ehib.org/emf/BrackenReport.pdf> (10 October 2013, date last accessed).
22. Meeker, J. D., Barr, D. B., Ryan, L., Herrick, R. F., Bennett, D. H., Bravo, R. and Hauser, R. *Temporal variability of urinary levels of nonpersistent insecticides in adult men*. J. Expo. Anal. Environ. Epidemiol. **15**, 271–281 (2005).