Bioelectromagnetics 23:196–205 (2002)
DOI 10.1002/bem.10002

Temporal Trends and Misclassification in Residential 60 Hz Magnetic Field Measurements

Robert S. Banks,[1]* William Thomas,[2] Jack S. Mandel,[1] William T. Kaune,[3] Sholom Wacholder,[4] Robert E. Tarone,[4] and Martha S. Linet[5]

[1]*Division of Environmental and Occupational Health, University of Minnesota School of Public Health, Minneapolis, Minnesota, USA*
[2]*Division of Biostatistics, University of Minnesota School of Public Health, Minneapolis, Minnesota, USA*
[3]*EM Factors, Richland, Washington, USA*
[4]*Biostatistics Branch, National Cancer Institute, NIH, Bethesda, Maryland, USA*
[5]*Radiation Epidemiology Branch, National Cancer Institute, NIH, Bethesda, Maryland, USA*

This research addressed the question of how well measurement data collected during a single visit, made at an arbitrary hour of day, day of week, and season, estimate longer term residential 60 Hz magnetic field levels. We made repeat spot and 24 h measurements in 51 children's home, located in the Detroit, MI, and the Minneapolis-St. Paul, MN metropolitan areas, on a regular bimonthly schedule over a 1 year period, as well as a single 2 week measurement, for total of eight visits, producing 21 days of data for each residence. We defined the long term estimate (LTE) as the geometric mean of all available 24 h geometric means from the first six bimonthly visits. The LTE served as the reference level for assessing seasonal, day of week, and diurnal effects, as well as the potential for misclassification. We found a small, but statistically significant ($P < .05$), seasonal effect, with levels approximately 3% lower than the LTE in the spring and about 4% greater during the summer. No effect was found for day of week. However, we did find a systematic and appreciable diurnal effect, suggesting that, for example, an evening spot measurement may overestimate the LTE by 20% or more. We also assessed how well the 24 h measurement from the last visit, which was not used in calculation of the LTE, estimated the LTE. We found a high degree of correlation ($r = .92$) and fair to good agreement using four exposure categories ($\kappa = .53$). Thus, the 24 h measurement appears to be a satisfactory LTE estimator. However, this finding must be interpreted with caution since considerable unexplained variability was present among the repeat 24 h measurements in about one-third of the homes. While the 2 week measurement does somewhat decrease exposure misclassification, its added intrusiveness and cost are likely to outweigh the improved precision. Bioelectromagnetics 23:196–205, 2002.

Key words: EMF; exposure assessment; children; methods; 24 h measurement; 2 week measurement

INTRODUCTION

The National Cancer Institute (NCI) and the Children's Cancer Group (CCG) undertook a comprehensive case-control investigation of the role of residential 60 Hz magnetic field exposure in the etiology of childhood acute lymphoblastic leukemia (ALL). This research project (the ''main study'' hereinafter) enrolled 638 newly diagnosed ALL cases, each under the age of 15 and resident of one of nine midwest and mid-Atlantic states, and 620 matched controls selected by random-digit dialing [Kleinerman et al., 1997; Linet et al., 1997].

Exposure assessment included indoor 60 Hz magnetic field measurements and wire coding of all residences that had been occupied by each subject for at least 6 months during the 5 year period prior to the reference date (defined as the date of diagnosis for the case and his or her individually matched control) and that met certain other criteria [Kleinerman et al., 1997].

Contract grant sponsor: National Cancer Institute; Contract grant number: N01-CP-05626.

*Correspondence to: Dr. Robert S. Banks, Robert S. Banks Associates, Inc., 1573 Fulham Street, St. Paul, Minnesota 55108-1313, 651 646 0452. E-mail: bobbanks@usinternet.com

Received for review 5 April 2000; revision received 2 August 2001

The research reported here, the NCI–CCG Pilot Study, Residential Electromagnetic Fields and Seasonal Variability (the "SV Study" hereinafter), was a methodological component of the main study. Its objective was to investigate how well measurement data collected during a single visit, made at an arbitrary time of day, day of week, and season, estimate longer-term residential 60 Hz magnetic field levels. To answer this question, we made repeat 60 Hz magnetic field measurements in children's homes on a regular bimonthly schedule over a 1 year period, as well as a 2 week measurement, for total of 8 visits, producing 21 days of data, to assess seasonal, day of week, and diurnal effects.

The 24 h measurement in the child's bedroom was of particular interest in our research. In an investigation of 64 control children, NCI–CCG investigators had found that these children spent a substantial percentage of their at home time in the bedroom (69% for children <9 years old; 79% for older children [Friedman et al., 1996]) and that time weighted average exposure at home is highly correlated with the 24 h measurement in their bedroom ($r = .97$) [Kleinerman et al., 1997]. Similarly, Koontz and Dietrich [1994] found that 48 h indoor measurements are highly correlated with at home personal exposure over the same time period ($r = .89$).

The NCI–CCG team also found that at home personal exposure is much more variable than that occurring away from home, but also that at home exposure is very highly correlated with total daily exposure ($r = .97$) [Kaune et al., 1994].

These results suggest that, on the day of measurement, a child's total daily exposure may be reliably estimated from a 24 h measurement in his or her bedroom. Our work was thus directed towards exploring an expanded question: "how stable and precise is that measurement as a predictor of longer term residential exposure?"

METHODS

Based on our design and under our supervision, Westat, Inc., Rockville, MD, was responsible for subject recruiting and data collection, as it was for the main study.

Subject Selection

Our protocol called for recruiting subjects from among main study control children who resided in either the Detroit, MI, or the Minneapolis-St. Paul, MN, metropolitan area. These children had been identified by random-digit dialing, with each child assigned the matching case's date of diagnosis as the reference date.

SV Study enrollment criteria included (1) eligible for, enrolled in, and participating in all components of the main study, which meant that the child had lived in his or her present home for at least 6 months prior to the reference date; (2) no plans for moving within 1 year after the first measurement visit; (3) residing in a home other than an apartment or mobile home; and (4) separately metered electrical service provided by either Detroit Edison Company or Northern States Power Company (Minneapolis-St. Paul).

To start our recruitment, Westat screened already enrolled main study control subjects to identify those meeting the above eligibility criteria. Mothers of eligible subjects were contacted by telephone for participation in the SV Study. If the mother was interested, the original Westat data collector scheduled our first measurement visit.

In addition, Westat recruited control subjects on an ongoing basis during main study measurement visits. In the latter situation, we were provided the measurement data, so that visit also served as our first measurement visit.

Because recruiting main study controls eligible and willing to participate in the SV Study proceeded slower than expected, we augmented enrollment with "specially recruited controls." These subjects were identified from families residing in either Detroit or Minneapolis-St. Paul that had been contacted earlier during main-study recruiting, and the mother had indicated that a child under the age of 15 resided in the home. However, the telephone interviewer had determined that the child was ineligible because he or she did not match the corresponding case closely enough in age to meet the eligibility requirement. Westat recontacted these families and invited them to participate in the SV Study.

Eligibility criteria for specially recruited control children were the same as for the main study controls, with three exceptions. At the time of recruiting, the index child 1) had to have lived in his or her present home for at least 16 months; 2) had to be frequency matched by age to the main study control subject distribution; and 3) had an assigned reference date that was 16 months prior to the date of telephone recruiting for the SV Study, to simulate the delay in matched control recruiting in the main study.

Mothers of both main study and specially recruited controls were offered a $100 incentive for participation, payable at $10/visit, with a larger payment following the final visit.

The study protocol called for enrolling 60 subjects, with the expectation that 50 would complete the study. Fifty eight subjects were actually enrolled, with seven later excluded (three found to be ineligible, two planned to move before all measurements could be completed, one presented major logistical problems, one refused further participation and parted way through data collection). Thus, the sample available for analysis consisted of 51 households (18 main study controls, 33 specially recruited controls; 27 Detroit, 24 Minneapolis-St. Paul).

Measurement Protocol

Our protocol for spot and 24 h measurements was identical to that of the main study, except that the two pregnancy bedroom spot measurements were not made. It consisted of a series of measurements made at standardized locations inside the residence with an Emdex-C electric and magnetic field data logging meter (Electric Field Measurement Company, West Stockbridge, MA). The Emdex-C is a small ($15.2 \times 11.9 \times 4.3$ cm), lightweight (624 gm), battery operated (single 9 V alkaline or lithium battery), self-contained, programmable instrument [Enertech, 1989a,b].

Prior to each measurement visit, the data collector verified operation of the instrument using a calibration coil set to produce a 1.5 μT magnetic field and checked each of the three channel (vector axis) sensors.

During the visit, the data collector made a series of seven spot measurements, uploaded the Emdex-C normal and low power spot measurement raw data file into an IBM compatible laptop computer. She then positioned the same Emdex-C for the 24 h measurement. Upon picking up the instrument the next day, she similarly uploaded the 24 h measurement data into the computer.

Spot Measurements. Each "spot" measurement consisted of 30 samples taken each 1 s over a 30 s period. Each spot measurement was made at the center of the largest open area in the room to be measured, at waist height with the Emdex-C Y axis vertical.

Normal power spot measurements were made at four locations: 1) index child's bedroom; 2) kitchen; 3) room, other than his or her bedroom and kitchen, where the child spent the most time ("third room" hereinafter); and 4) immediately outside the front door. Rooms were identified according to their use during the reference year. Mothers were asked to turn on electric appliances that were usually in use when the child was in each of the three rooms during the reference year.

Low power spot measurements were made in the same locations, except at the front door, with all lights and appliances turned off, except for three incandescent lights. The thermostat (heating or cooling) was set at the nighttime level.

Twenty Four Hour Measurement. The 24 h measurement consisted of 2880 samples taken each 30 s over a 24 h period in the child's bedroom. The data collector placed the Emdex-C in a sealed plastic box with the instrument's Z-axis vertical and left the box at a location, typically, under the child's bed, where the magnetic field was of the same level (± 0.02 μT) as measured at the location of the child's torso when sleeping.

Two Week Measurement. The 2 week measurement consisted of 4032 samples taken each 300 s over the 336 h period. An Emdex-C was placed at the same location where the 24 h measurement was made. When the data collector returned after 2 weeks to pick up the Emdex-C, she uploaded the measurement data into her laptop computer.

Wiring Configuration Coding. During a separate visit, a trained technician made a standardized diagram of all transmission, primary and secondary distribution, and service drop wiring within 45.7 m of the residence. Information from the diagram later served as input to a computerized algorithm that classified the residence according to the five level adaptation of the Wertheimer–Leeper wiring configuration code [after Barnes et al., 1989].

Measurement Schedule

Bimonthly Measurement Visit. Spot and 24 h 60 Hz magnetic field measurements were made bimonthly seven times over a 1 year period. The intent was for each SV Study bimonthly measurement visit to simulate a main study visit.

If the mother had been recruited for the SV Study during the main study visit, that visit also served as our first bimonthly measurement visit. Otherwise, our first visit was scheduled at the convenience of the mother. During the first visit, the data collector administered a structured questionnaire to the mother to obtain additional demographic information and data on residence characteristics (electric utility account information, exterior siding material, heating source, use of air conditioning, etc.).

Subsequent bimonthly measurement visits were preferably scheduled within 1 week (but no more than ± 30 days) of successive 2 month anniversaries of the first visit. In any case, the next visit was never scheduled within 30 days of the previous visit. The seven bimonthly measurement visits are termed the "A, B, C,... G Visits," respectively. A missed visit did not change the designation; e.g., the G Visit was always on the (approximately) 1 year anniversary of the A Visit.

Two Week Measurement Visit. Immediately after one of the bimonthly visits, a 2 week measurement was made in the child's bedroom. No restrictions were imposed on scheduling the 2 week measurement visit, which was termed the "Z Visit."

Data Collection

Data collection started on March 2, 1992 and was completed on August 22, 1994. Among the 51 households completing the study, eight bimonthly measurement visits were missed. In addition, Emdex-C raw data files from two normal and low power spot and three 24 h measurements were corrupted. The data set available for analysis included 347 out of a possible 357 (97.2%) complete sets of normal and low power spot measurements, 346 out of a possible 357 (96.9%) days of 24 h measurement, and 714 out of a possible 714 (100%) days of 2 week measurement.

With the exception of one household that missed the last two visits, no more than one visit was missed for any one household, and all had 2 week measurements and wiring configuration coding. Figure 1 shows the longitudinal distribution of the bimonthly and 2 week measurement visit start dates.

ANALYSIS

Data Reduction

The i-th Emdex-C sample from a measurement's raw data file consisted of the three magnetic flux density vector axis readings, Bx_i, By_i, and Bz_i, in milligauss (mG). All analyses used the resultant vector magnitude in microtesla (μT), calculated as follows:

$$B_i = \left(\frac{\sqrt{(Bx_i + 0.05)^2 + (By_i + 0.05)^2 + (Bz_i + 0.05)^2}}{10} \right) \mu\text{T}.$$

The Emdex-C had a resolution of 0.1 mG; the 0.05 additive factor was a round-off correction.

For each measurement, a number of descriptive statistics were calculated from the B_i terms. However, for reasons discussed below, only the geometric mean and standard deviation were used in further analysis.

In addition, for the 24 h and 2 week measurements, clock hour arithmetic means (with first hour wrap-around to the last) were also computed. So that 24 h and 2 week measurement statistics could be combined in the same analysis, 24 h measurement Emdex-C raw data files were alternatively reduced in a fashion that simulated the 300 s sampling interval of the 2 week measurements.

Because of the skewness in the 60 Hz magnetic field measurements, arithmetic means can be misleading. A conventional statistical approach to analyzing highly skewed data is use of rank methods, such as the logarithmic scale and Spearman correlations. Consequently, with one exception, all results are presented herein as geometric means and their 95% confidence intervals. Geometric statistics have been presented in other newer research [e.g., Kaune and Zaffanella, 1994; Kaune et al., 1994; Koontz and Dietrich, 1994; Vistnes et al., 1997; Deadman et al., 1999]. The exception is the diurnal analysis, for which only clock hour arithmetic means were available.

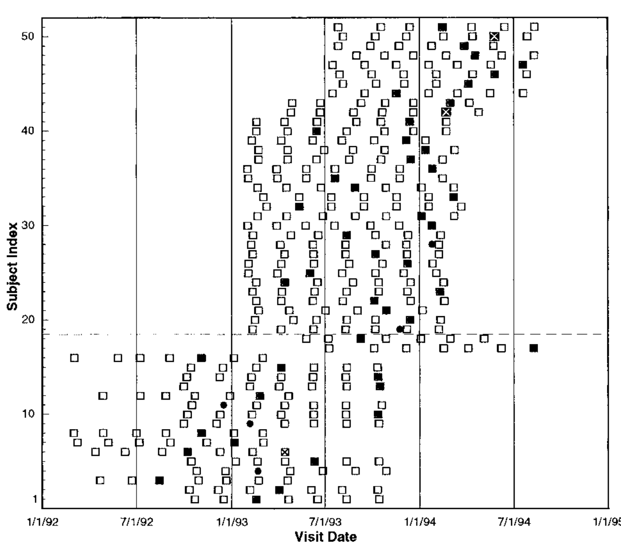

Fig. 1. Calendar dates of 24 h (A–G Visits) measurements (open squares) and start of 2 week (Z Visit) measurements (black circles). Of the 357 possible 24 h measurements from A–G Visits, 8 were not scheduled and 3 had corrupted data files (squares with "X"). All 51 2 week measurements were made. Subjects 1–18 were main study controls, and 19–51 were specially recruited controls.

Long Term Estimate

We defined the long term estimate (LTE) for each household as the geometric mean of all available 24 h geometric means from the first six bimonthly measurement (A–F) visits. The LTE was used as the reference level for analysis purposes.

For each household, the LTE was computed as follows:

$$\text{LTE}_j = \log^{-1} \left[\frac{\sum_{k=1}^{N_j} \log\left(Y1\text{d}_{jk}\right)}{N} \right] \mu\text{T},$$

where j is the household index ($j = 1–51$), and k is the 24 h measurement chronological index ($k = 1–6$ for the A–F Visits, respectively). The G Visit 24 h measurement was excluded for two reasons. 1) It was from a wrap-around visit and would therefore doubly weigh the 2 month period in which it was made; and 2) it was used as an estimator independent of the LTE. For the six households missing one A–F Visit, $N_j = 5$, while $N_j = 6$ for the other 45 residences.

Temporal Trend Estimates

Seasonal. We estimated the average seasonal effect by fitting a nonparametric smooth curve to the residual differences formed by subtracting the residence LTE from all available 24 h geometric means from the A–G Visits ($n = 346$). The curve was generated with the S-Plus function, KSMOOTH [Statistical Sciences, 1995], with a Gaussian kernel. For a discussion of such models, see, e.g., Hastie and Tibshirani [1990]. Smoothing bandwidths were chosen by cross validation, in which all observations from a single house were omitted, thus making no assumptions about the underlying correlation structure [Rice and Silverman, 1991; Diggle et al., 1994].

This estimate averaged Detroit and Minneapolis-St. Paul residences and the corresponding dates for the three calendar years of observation. In order to match the estimates at the beginning and end of the year, 60 residuals were repeated at each end to extend the curve estimate.

Day of Week. We estimated day of week differences from all available 24 h geometric means from A–G and Z Visits ($n = 1060$), using a random effects linear model to estimate the least squares means for the days of the week. The regression model included a random intercept for each residence, estimated seasonal effect and day of week. For a discussion of such models, see, e.g., Diggle et al. [1994], Chapter 4.

Diurnal. We estimated diurnal effects using all available clock hour arithmetic means from A–G and Z Visits ($n = 25{,}440$), using a random effects linear model to estimate the least-squares means for each of the 24 clock hours. The regression model included a random intercept for each residence, estimated seasonal effect, and hour of day.

LTE Estimators

Of interest here was the ability of single visit measurement data to estimate the LTE. The last G Visit 24 h geometric mean, $\mathrm{Y1d}_{j7}$ (Y1d hereinafter) ($n = 46$) was the basic measurement under evaluation. For comparative purposes, however, we also examined shorter and longer measurement durations as exposure surrogates: the G Visit normal power spot measurement, child's bedroom, geometric mean, $\mathrm{NPS\_CB}_{j7}$ (NPS_CB hereinafter) ($n = 47$) and the 2 week measurement geometric mean,

$$Y14\mathrm{d}_j = \log^{-1}\left(\frac{\sum_{k=8}^{21} \log\left(Y1\mathrm{d}_{jk}\right)}{14}\right)\mu\mathrm{T}$$

[Y14d, hereinafter] ($n = 51$), where $k = 8$ is the chronological index for the first day of the 2 week measurement. Note that G and Z Visit measurement data were not used in calculation of the LTE.

RESULTS

Geometric means and 95% confidence intervals for the 24 h and each of the seven spot 60 Hz magnetic field measurement from the E Visit and for the LTE are presented in Table 1, for all subjects and for both subject subsamples. In addition, we compared the subsample distributions, using the Student's *t*-test for equality of means from independent samples, under the assumption of equal variance. We found no difference for any of the individual measurements or for the LTE (Table 1). Further, there was no difference in the distribution of the five-level Wertheimer–Leeper wire code ($\chi^2 = 6.03$, 4 df, $P = .20$; data not shown). Table 2 presents measurement correlation coefficients, again from the E Visit.

Similar results were obtained using measurement data from other visits (data not shown). These findings led us to conclude that the two subsamples are from the same underlying population.

Temporal Trend Estimates

Seasonal. Using random effects linear modeling, we found a small, but statistically significant ($P < .05$), seasonal effect on the 24 h geometric means. A smoothed estimate of the seasonal effect (Fig. 2) shows a decrease of less than 3% from the LTE in the spring (February–May), an increase of about 4% during the summer (June–September), and virtually no effect in the fall and early winter (October–January). This effect was consistent between Detroit and Minneapolis-St. Paul and across all three years of data collection.

Day of Week. We found no significant effect of day of week on the 24 h geometric means, with or without adjustment for seasonal effect (Fig. 3). There was no significant difference between weekdays ($n = 837$) and weekend days ($n = 223$).

Diurnal. Figure 4 shows the strong and significant effect of the hour of the day on the clock hour

TABLE 1. Sixty Hertz Magnetic Field Measurement Geometric Means (and 95% Confidence Intervals), With Comparison by Subject Source, E Visit

Measure	All SV Study residences, μT ($n=51$)	A Main study control residences, μT ($n=18$)	B Specially recruited control residences, μT ($n=33$)	A/B Geometric means ratio	P*
Long term estimate	0.094 (0.074, 0.119)	0.091 (0.058, 0.142)	0.096 (0.072, 0.128)	0.944 (0.573, 1.556)	.82
24 h	0.097 (0.077, 0.123)	0.097 (0.061, 0.154)	0.097 (0.073, 0.130)	0.993 (0.600, 1.644)	.98
Normal power spot					
Child's bedroom	0.096 (0.072, 0.128)	0.089 (0.055, 0.146)	0.100 (0.069, 0.144)	0.895 (0.492, 1.629)	.71
Kitchen	0.126 (0.098, 0.161)	0.118 (0.077, 0.179)	0.130 (0.095, 0.179)	0.903 (0.537, 1.519)	.69
Third room	0.110 (0.083, 0.145)	0.098 (0.058, 0.167)	0.117 (0.083, 0.164)	0.845 (0.469, 1.522)	.57
Front door	0.097 (0.075, 0.124)	0.106 (0.066, 0.171)	0.092 (0.068, 0.125)	1.157 (0.681, 1.966)	.58
Low power spot					
Child's bedroom	0.087 (0.066, 0.114)	0.083 (0.049, 0.143)	0.089 (0.064, 0.123)	0.941 (0.527, 1.681)	.83
Kitchen	0.126 (0.098, 0.161)	0.119 (0.075, 0.188)	0.129 (0.095, 0.176)	0.921 (0.547, 1.552)	.75
Third room	0.099 (0.075, 0.131)	0.084 (0.050, 0.143)	0.108 (0.076, 0.152)	0.785 (0.434, 1.420)	.42

*t-test for equality of means from independent samples, assuming equal variance, 49 df, two-tailed test.

arithmetic means, relative to the residence LTE. Of the three temporal effects, the diurnal effect is by far the largest.

LTE Estimators

Correlation Coefficients. We found a high degree of correlation between the NPS_CB (G Visit normal power spot measurement, child's bedroom), Y1d (G Visit 24 h measurement), and the Y14d (2 week measurement) and the LTE ($r = .90, .92, .94$, respectively). The relationship between the Y1d and the LTE is shown in Figure 5. We found very similar regression lines for the other two estimators (data not shown).

Misclassification. To examine the precision by which the each of three estimators correctly classifies residences, we cross-tabulated NPS_CB, Y1d, and Y14d with the LTE, using exposure cut points based on quartiles of the LTE distribution (< 0.050, 0.050–0.114, 0.115–0.159, ≥ 0.160 μT).

The results for Y1d ($n = 46$) are shown in Table 3. With the kappa statistic [Fleiss, 1981], we found fair to good agreement between the Y1d and the LTE ($\kappa = .53$). However, about one-third (16/46; 35%) of the observations differed from their corresponding LTE category (Table 3). Among the 16 that were misclassified, five had a Y1d greater than their LTE (i.e., Y1d overestimates LTE) and 11 had a lower Y1d (underestimates). Only one residence was characterized by a 24 h measurement that differed by more than one exposure category from its LTE.

For the NPS_CB estimator ($n = 47$), we found about the same misclassification rate (17/47; 36%). However, three observations differed from their LTE by more than one exposure category ($\kappa = .51$) (data not shown).

Using the Y14d estimator ($n = 46$), the misclassification rate was somewhat lower (16/51; 31%)

TABLE 2. Spearman Rank Order Correlation Coefficients for Relationship Between 60 Hz Magnetic Field Measurements, E Visit ($n = 51$)

			Normal power spot				Low power spot	
Measurement	Long term estimate	24 h	Child's bedroom	Kitchen	Third room	Front door	Child's bedroom	Kitchen
Normal power spot								
Child's bedroom	.73	.73						
Kitchen	.77	.73	.63					
Third room	.73	.76	.65	.80				
Front door	.75	.80	.64	.76	.84			
Low Power Spot								
Child's bedroom	.87	.85	.77	.72	.72	.74		
Kitchen	.77	.73	.62	.86	.72	.71	.84	
Third room	.72	.74	.62	.73	.91	.75	.81	.82

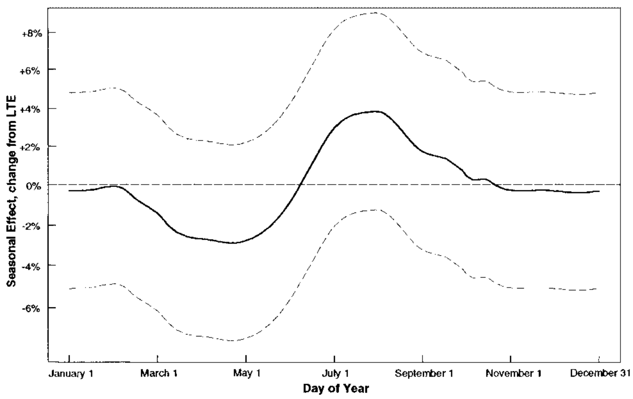

Fig. 2. Smoothed estimate of average seasonal effect (solid curve) and 95% confidence intervals (dashed curves). The horizontal axis represents calendar date, combining the three study years, 1992–1994, and the vertical axis shows the average percent change from the LTE, with 0% indicating no effect. A cosine regression model fit to the data has an amplitude significantly different from zero ($P < .05$).

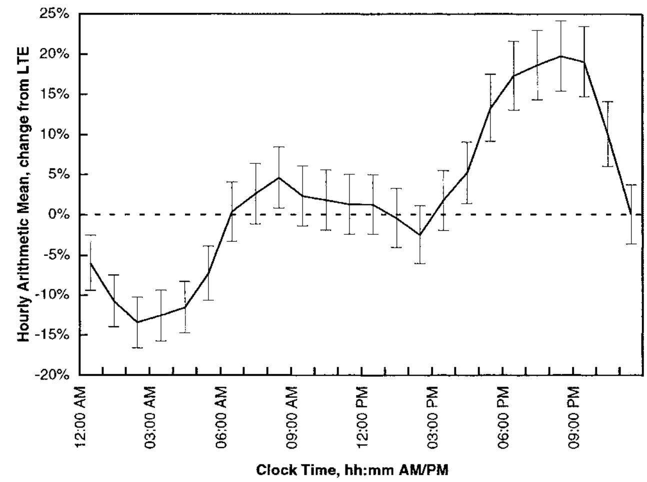

Fig. 4. Hourly estimates of diurnal effect and 95% confidence intervals, seasonally adjusted. The vertical axis shows the arithmetic-mean percent change from the LTE, with 0% indicating no change.

(data not shown) than for the Y1d estimator. As with the Y1d estimator, only one observation differed from its LTE by more than one exposure category ($\kappa = .58$).

DISCUSSION

The SV Study is one of first detailed investigations of residential 60 Hz magnetic field levels with multiple measurements in each residence. The measurements were repeated on a regular bimonthly schedule in over 50 homes.

As discussed below, we found that the 24 h measurement is a fairly reliable estimator of time weighted average annual exposure levels. However, since this is a residence—not a subject—measurement, the utility of this finding is inherently limited to residentially stable subjects.

Temporal Trend Estimates

Earlier literature had speculated but provided no supporting data that a seasonal effect in northern U.S. climates may be appreciable and could be an important

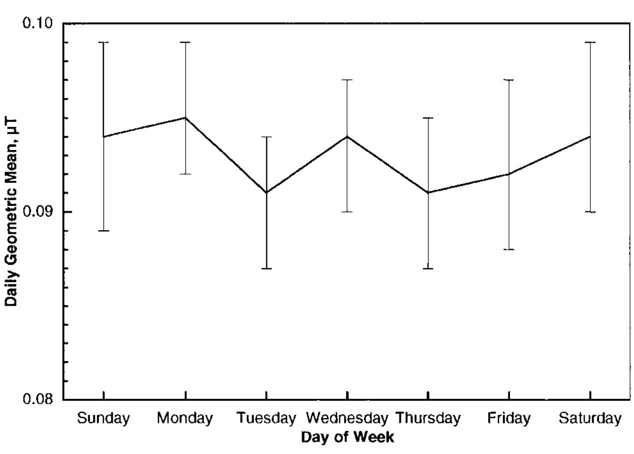

Fig. 3. Daily estimates of day of week effect and 95% confidence intervals, using adjusted least squares 24 h and 2 week daily geometric means ($n = 1060$).

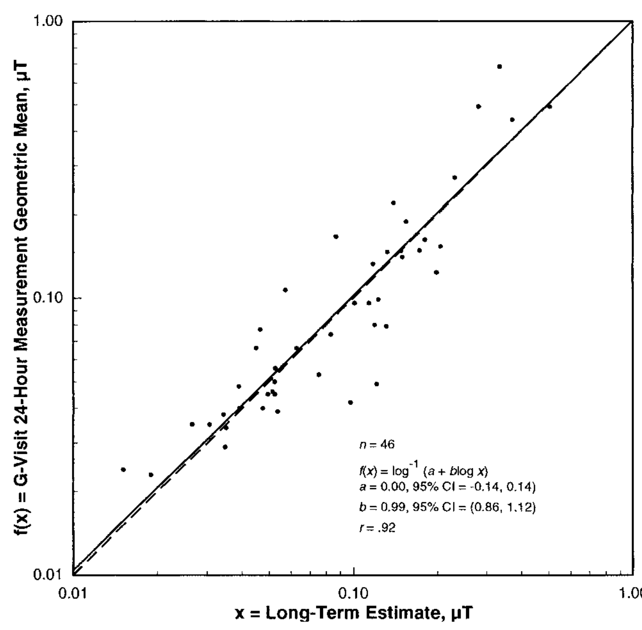

Fig. 5. Simple linear regression of G Visit 24 h measurement geometric mean on the LTE. Solid line: $f(x) = \log^{-1}(a + b \log x)$; dashed line: $f(x) = x$.

TABLE 3. Residential Long Term Estimate Versus Independent 24 h 60 Hz Magnetic Field Measurement Geometric Mean (G Visit), Using LTE Quartile Exposure Cutpoints ($n = 46$)

	Long term estimate				
24 h measurement	< 0.050 μT	0.050–0.114 μT	0.115–0.159 μT	≥ 0.160 μT	Total
< 0.050 μT	11	4	1	0	16
0.050–0.114 μT	2	8	3	0	13
0.115–0.159 μT	0	0	4	3	7
≥ 0.160 μT	0	1	2	7	10
Total	13	13	10	10	46
No. (%) misclassified	2 (15%)	5 (38%)	6 (60%)	3 (30%)	16 (35%)

confounder in case-control studies [cf., Miller et al., 1997; Portier and Wolfe, 1998]. For example, in their literature review, Miller et al. [1997] note that while the main study incorporates "notable improvements over previous work," it also "raises two major methodological questions." One of these is that "a 24 hour bedroom measurement may not be adequate for an annual average in the current or previous year. No information is presented for seasonal variation (appreciable in the midwestern and eastern states studied)." At the time, however, there were insufficient data in the scientific literature to either confirm or refute Miller and her colleagues' contention of "appreciable" seasonal variation in 60 Hz magnetic field levels in the main study residences.

Our findings do not support this speculation. We found only a small (−3 to +4%) seasonal effect, which does not explain and is negligible in the face of the variability among repeat 24 h measurements evident in Figure 6. Consequently, we find no basis to recommend seasonal constraints on residential 60 Hz magnetic field measurements in case-control studies.

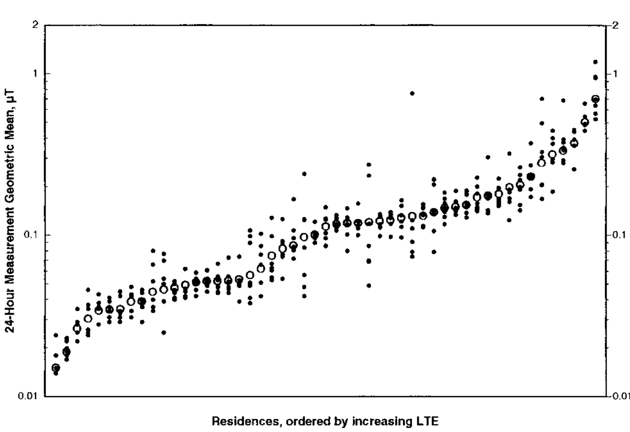

Fig. 6. Variability of 24 h (A–G Visits) measurement geometric means about the LTE. The 24 h geometric means (black circles) are grouped by residence in a vertical line. Residences are ordered by increasing LTE (open circles) on the horizontal axis.

It is possible that Miller et al. [1997] were assuming that utility loading may be responsible for any seasonal variability in residential 60 Hz magnetic field levels. Our results provide only partial support for this suggestion. The two utilities are both summer peaking, with maxima in July–August due to air conditioning loads. Figure 2 appears to track this pattern. However, the decrease in February–May, also evident in Figure 2—with a minimum magnitude almost as large as the summer maximum—is unexplained by utility load profiles. In depth and long term source, characterization will be necessary to explain this temporal variability.

Interestingly, our seasonal effect differs from that reported by Deadman et al. [1999]. These researchers made 48 h personal exposure measurements on 382 Canadian children in five provinces, finding that arithmetic mean exposures were higher in the "winter" (November–March) than in the "summer" (April–October): 0.137 μT, 95% CI = (0.114, 0.160 μT) and 0.109 μT, 95% CI = (0.096, 0.123 μT), respectively. Following the reasoning presented earlier in this discussion, we can assume the 24 h bedroom measurement is highly correlated with a child's total daily exposure and therefore conclude that Deadman et al.'s [1999] results are seasonally inverted from ours. The effect was strongest in Québec, where 71% of homes have electric space heating. In our study, only one home was electrically heated, and this may explain the difference. Like us, Deadman et al. [1999] found no day of week effect.

There is no evidence for a day of week or a weekday versus weekend day effect (Fig. 3). Therefore, it is not necessary to impose constraints on the day of measurement in case-control studies. On the other hand, the substantial and statistically significant diurnal effect on the 1 h arithmetic means (Fig. 4) suggests that walk-in spot measurements, which can be made at any time of the day, may introduce errors in estimation of the LTE. For example, a spot measurement in the child's bedroom made in the evening may overestimate the LTE by 20% or more (Fig. 4).

LTE Estimators

On the basis of correlation coefficients, the Y1d appears to be excellent estimator of the LTE. With the kappa statistic, however, we found only fair to good agreement between the Y1d and the LTE. This latter finding reflects the large potential for misclassification with the 24 h measurement, as shown in Table 3.

Figure 6 shows individual 24 h geometric means by residence, ordered by increasing LTE. Using the ratio of the maximum to the minimum mean as a practical index of the range of measurements that may be expected from any one household, we found one residence with a max/min ratio of 10.2. We examined the outlier maximum—0.757 μT measured on June 9, 1993 in a Minneapolis-St. Paul home—verifying that the Emdex-C data file was not corrupted. All other residences had max/min ratios less than 6.0, with almost two-thirds (33/51; 65%) having max/min ratios less than 2.0, indicating relatively small within home variability. However, the considerable (2 to 6-fold) unexplained variability among repeat 24 h measurements in the other third of the residences is of concern.

Our results suggest that LTE estimation can be somewhat improved with longer duration measurements. While the Y14d does improve agreement with the LTE, it is certainly not clear that the somewhat greater precision outweighs the added intrusiveness and cost of the longer measurement.

Examination of Figure 1 suggests that G Visits may be underrepresented in the fall and early winter (October–January), the period when the seasonal effect is minimal (October–January; Fig. 2). If so, the effect would be underestimation of the predictive value of a single 24 h measurement. As Table 4 indicates, the G Visits were not uniformly distributed across the year; indeed, there were none in November–December. On the other hand, 13 of the 17 of the January–Febuary dates were in February, a month during which there is a decreasing seasonal effect (Fig. 2). These observations lessen the confidence that can be placed in the 24 h measurement as an LTE estimator. However, the seasonal effect is small, and this finding should have little practical impact.

TABLE 4. Calendar Date Distribution of G Visits by Calendar Month ($n = 46$)

Month	Actual
January	4
February	13
March	8
April	3
May	1
June	0
July	4
August	3
September	0
October	10
November	0
December	0

Limitations

While the results from the SV Study provide considerable useful direction for future EMF exposure assessment and epidemiologic research, a number of possible determinants of residential 60 Hz magnetic field levels were not fully characterized. Further research is necessary to determine the effect on the LTE of geographical and climatic factors (high air conditioning loads, prevalent electric heating, etc.); distribution system engineering practice; neighborhood age, housing stock characteristics, and density; and other factors.

In addition, the study period was only 1 year. It would be helpful to study the reproducibility of residential 60 Hz magnetic field measurements over multiple years, since case-control studies typically use exposure measurements taken long after the etiologic period.

CONCLUSION

In summary, we found a small, but statistically significant ($P < .05$) seasonal effect, but likely of little practical importance; no day of week effect; and a systematic diurnal effect.

The correlation and kappa statistics both indicate that all three measurements are reasonable estimators of the LTE, with some improvement with increasing measurement duration. However, we do not recommend the walk-in spot measurement (NPS_CB) because of diurnal variability. At the same time, the added intrusiveness and cost are likely to outweigh the marginal improvement in exposure classification provided by the 2 week measurement (Y14d).

Thus, our findings support the use of 24 h measurement in the child's bedroom (Y1d) as an estimator of annual time weighted average exposure level. This conclusion can be expected to be applicable in the United States and Canada; different residential distribution system engineering and in home wiring practices may impact its applicability elsewhere.

ACKNOWLEDGMENTS

We thank Dr. Richard K. Severson, Michigan Cancer Foundation, Detroit, for his guidance in the early stages of study design; Richard Iriye, Enertech Consultants, Inc., Campbell, CA, for Emdex-C data reduction software support; Carol Haines and Bob McConnell, Westat, Inc., Rockville, MD, for continuing assistance with integrating and coordinating this research with the main study, as well as adaptation of main study data management support software (McConnell); special thanks are due to Kathy Deutchman, Elk River, MN, Barbara A. Hood, Manitou Beach, MI, and Patricia P. Mueller, Minneapolis, MN. We also thank the three Westat data collectors assigned to the SV Study, for their patience in implementing the intricate data collection requirements of this research. In addition, we acknowledge the many helpful suggestions made by the anonymous reviewers, which have greatly improved the presentation in this paper. Finally, the gracious cooperation of our subjects' families deserve special mention. The protocol was intrusive, involving eight measurement visits over the course of 1 year, with seven requiring the data collector to be on the premises on 2 consecutive days.

REFERENCES

Barnes F, Wachtel H, Savitz D, Fuller J. 1989. Use of wiring configuration and wiring codes for estimating externally generated electric and magnetic fields. Bioelectromagnetics 10:13–21.

Deadman J-E, Armstrong BG, McBride ML, Gallagher R, Thériault G. 1999. Exposures of children in Canada to 60-Hz magnetic and electric fields. Scand J Work Environ Health 25:368–375.

Diggle PJ, Liang K-Y, Zeger SL. 1994. Analysis of longitudinal data. New York: Oxford University Press.

Enertech. 1989a. EMDEX system manuals (vol 1): User's manual. Report EPRI EN-6518. Palo Alto, California: Electric Power Research Institute. Prepared by Enertech Consultants, Inc.

Enertech. 1989b. EMDEX system manuals (vol 2): Technical reference manual. Report EPRI EN-6518. Palo Alto, California: Electric Power Research Institute. Prepared by Enertech Consultants, Inc.

Fleiss JL. 1981. Statistical methods for rates and proportions. New York: John Wiley & Sons. ISBN 0 471 06428 9. 321 p.

Friedman DR, Hatch EE, Tarone R, Kaune WT, Kleinerman RA, Wacholder S, Boice JD Jr., Linet MS. 1996. Childhood exposure to magnetic fields: residential area measurements compared to personal dosimetry. Epidemiology 7:151–155.

Hastie TJ, Tibshirani RJ. 1990. Generalized additive models. New York: Chapman and Hall.

Kaune WT, Zaffanella LE. 1994. Assessing exposures of children to power-frequency magnetic fields. J Exp Anal Environ Epidemiol 4:149–170.

Kaune WT, Darby SD, Gardner DN, Hrubec Z, Iriye RN, Linet MS. 1994. Development of a protocol for assessing time-weighted-average exposures of young children to power-frequency magnetic fields. Bioelectromagnetics 15:33–51.

Kleinerman RA, Linet MS, Hatch EE, Wacholder S, Tarone RE, Severson RK, Kaune WT, Friedman DR, Haines CM, Muirhead CR, Boice JD Jr., Robison LL. 1997. Magnetic field exposure assessment in a case-control study of childhood leukemia. Epidemiology 8:575–583.

Koontz MD, Dietrich FM. 1994. Variability and predictability of children's exposure to magnetic fields. J Exp Anal Environ Epidemiol 4:287–307.

Linet MS, Hatch EE, Kleinerman RA, Robison LL, Kaune WT, Friedman DR, Severson RK, Haines CM, Hartsock CT, Niwa S, Wacholder S, Tarone RE. 1997. Residential exposure to magnetic fields and acute lymphoblastic leukemia in children. N Engl J Med 337:1–7.

Miller RD, Neuberger JS, Gerald KB. 1997. Brain cancer and leukemia and exposure to power-frequency (50-to-60-Hz) electric and magnetic fields. Epidemiol Rev 19:273–293.

Portier CJ, Wolfe MS (eds). 1998. Assessment of health effects from exposure to power-line frequency electric and magnetic fields. NIEHS working group report. Report No. 98-3981. Research Triangle Park, North Carolina: National Institute of Environmental Health Sciences, U.S. National Institute of Health. 522 p.

Rice JA, Silverman BW. 1991. Estimating the mean and covariance structure nonparametrically when the data are curves. J R Stat Soc (Series B) 53:233–243.

Statistical Sciences. 1995. S-PLUS users manual. Seattle, Washington: Statistical Sciences, Inc.

Vistnes AI, Ramberg GB, Bjornevik LR, Tynes T, Haldorsen T. 1997. Exposure of children to residential magnetic fields in Norway: is proximity to power lines an adequate predictor of exposure? Bioelectromagnetics 181:47–57.