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Development of a Protocol for Assessing Time-Weighted-Average Exposures of Young Children to Power-Frequency Magnetic Fields

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A study was carried out in 1990 to guide the development of a protocol for assessing residential exposures of children to time-weighted-average (TWA) power-frequency magnetic fields. The principal goal of this dosimetry study was to determine whether area (i.e., spot and/or 24 h) measurements of power-frequency magnetic fields in the residences and in the schools and daycare centers of 29 children (4 months through 8 years of age) could be used to predict their measured personal 24-h exposures. TWA personal exposures, measured with AMEX-3D meters worn by subjects, were approximately log-normally distributed with both residential and nonresidential geometric means of 0.10 µT (1.0 mG). Between-subjects variability in residential personal exposure levels (geometric standard deviation of 2.4) was substantially greater than that observed for nonresidential personal exposure levels (1.4). The correlation between log-transformed residential and total personal exposure levels was 0.97. Time-weighted averages of the magnetic fields measured in children's bedrooms, family rooms, living rooms, and kitchens were highly correlated with residential personal exposure levels (*r* = 0.90). In general, magnetic field levels measured in schools and daycare centers attended by subjects were smaller and less variable than measured residential fields and were only weakly correlated with measured nonresidential personal exposures. The final measurement protocol, which will be used in a large US study examining the relationship between childhood leukemia and exposure to magnetic fields, contains the following elements: normal- and low-power spot magnetic field measurements in bedrooms occupied by subjects during the 5 years prior to the date of diagnosis for cases or the corresponding date for controls; spot measurements under normal and low power-usage conditions at the centers of the kitchen and the family room; 24-h magnetic-field recordings near subjects' beds; and wire coding using the Wertheimer-Leeper method. ©1994 Wiley-Liss, Inc.*

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INTRODUCTION

Even though acute lymphocytic leukemia (ALL) is the most common childhood neoplasm in western countries, its etiology is poorly understood. The only risk factors consistently associated with childhood ALL are pregnancy-related diagnostic X-ray exposures and post-natal high-dose exposures to ionizing radiation [Neglia and Robison, 1988]. Recently, various environmental exposures (including residential proximity to nuclear power plants, home-related use of pesticides, radon exposures, proximity to very high current configuration power lines, and others) have been linked with ALL, but the studies reporting these associations have been generally small and the findings inconsistent [Napalkov, 1986; Lowengart et al., 1987; Wertheimer and Leeper, 1979; Savitz et al., 1988; London et al., 1991]. To further evaluate many of these and other suspected risk factors, a large, multistate, broad-based case-control study of ALL in children under age 15 was undertaken collaboratively by the Children’s Cancer Group (CCG) and the Epidemiology and Biostatistics Program at the National Cancer Institute (NCI). Among the postulated risk factors under investigation is exposure to power-frequency magnetic fields.

It is not known what aspect of magnetic field exposures (if any) is most directly related to health outcomes in human populations, nor have school and daycare exposures of children been systematically investigated. Consequently, while there has been considerable discussion of alternative definitions of magnetic field exposure [Morgan, 1989; Armstrong et al., 1990; Morgan and Nair, 1992], there is no consensus at this time as to how (and where) exposure should be defined and measured. In view of this uncertainty, the time-weighted-average (TWA) residential magnetic field was selected as the primary measure of exposure in this study. This choice echoes similar choices made by other research groups [Wertheimer and Leeper, 1979; Savitz et al., 1988; Severson et al., 1988; London et al., 1991; Feychting and Ahlbom, 1992]. Perhaps the most direct support for the selection of TWA exposure comes from the last of these studies: Feychting and Ahlbom found an association between leukemia incidence in children living in residences within 300 m of transmission lines and historical exposure, estimated by using historical transmission-line load data to calculate TWA magnetic fields produced by nearby transmission lines.

The major objective of the current dosimetry study, carried out from April-August, 1990 in the greater metropolitan Washington, DC, area, was to determine what subset of area measurements, made throughout subjects’ residences, schools, and daycare centers, could best approximate their measured 24-h time-weighted-average (TWA) personal exposures to magnetic fields. The results of this study were used to guide the development of the protocol that will be used in the CCG/NCI study to assess exposures of children to power-frequency magnetic fields.

MATERIALS AND METHODS

Subjects

The subjects of the dosimetry study were 29 children, ages 4 months through 8 years, who resided in the greater metropolitan Washington, DC, area. The dosimetry study included a large number of measurements and required a substantial time commitment. Since a high degree of compliance with the complex study protocol was needed, volunteer families were recruited from employees of Westat Inc. and NCI and from an area private daycare facility. The use of volunteer subjects was thought to be appropriate because the study objective was to evaluate relationships between. personal exposure measurements and various surrogate measures of magnetic field exposure, rather than to characterize the exposure of the typical child to power frequency magnetic fields. To provide data related to socioeconomic status, we collected information on the educational levels of subjects' parents.

Locations of Measurements

Residences. Eligible subjects resided in single-family homes served by overhead electric wiring and with internal wiring protected by circuit breakers rather than fuses. These eligibility criteria were chosen to enable preliminary evaluation of the Wertheimer-Leeper (WL) wire coding system (described later) as a surrogate measure for residential personal exposure and to prevent the measurement equipment from overloading fuse-protected circuits.

Schools and daycare centers. Subjects attended a variety of public and private schools and daycare centers (hereafter termed "schools"). Permission to take measurements within school facilities was obtained directly from the principals of private schools and the superintendents of public schools. Permission to take measurements in public schools required several visits to the central administration offices and consultation with local public health authorities.

Personal Exposure Level Measurements

Personal exposure meter. An individual's time-weighted-average (TWA) exposure to power-frequency magnetic fields is best measured at present by an exposure meter that is worn by the subject for as long an interval as possible and which samples and stores frequent measurements of the magnetic field at the meter's location. However, meters of this type that were available at the time of the study were deemed too heavy to be worn by small children. Instead, AMEX-3D meters were selected. These meters are small (2.7 cm x 5.1 cm x 10.2 cm), lightweight (120 g), battery-powered, integrating meters that measure, with an accuracy of ±20%, cumulative personal exposure, X, to a three-dimensional magnetic field. The "memory" of an AMEX-3D is nonvolatile: it can be turned off without losing data and can be subsequently turned back on to measure additional exposure. AMEX-3D meters are described in detail elsewhere [Kaune et al., 1992].

Protocol for personal exposure measurements. A 24-h personal exposure measurement obtained using the AMEX-3D was chosen to be the benchmark against which spot and other surrogate measurements were compared. The benchmark, referred to throughout this report as a personal exposure level, is the TWA exposure level. B_{exp}, defined by $B_{exp} = X/T$, where T is the total time the meter was turned on.

Each subject was asked to wear AMEX-3D personal exposure meters for 24 h on a typical weekday including times at school and/or daycare. Two meters were provided to each subject, one to be worn or placed immediately next to the subject while he or she was at home, the other to be similarly worn or placed when the subject was not at home. While the details of the protocol were being carefully explained to the parents, the children were encouraged to become familiar with the meter to increase compliance with wearing it and to prevent them from attempting to later remove it from the carrying pouch. Meters were worn in pouches which were sewn to suspenders or belts or were secured in large soft fabric cubes kept next to infants. When the subject was sleeping or playing contact sports, the suspenders or belt was taken off and kept in locations as close to the subject as possible.

Special neon-colored cards were placed on the insides of all exit doors in the residence to remind parents and subjects to change from one to the other personal exposure meter whenever a subject left or returned to his or her residence. The meter that was worn was always turned on; the meter not worn was turned off. During the 24-h period the personal exposure meters were worn, parents recorded in an activity diary the locations within and immediately outside the home and the away-from-home locations where subjects spent 15 min or longer. The following locations were defined in the diary: subject's bedroom, other bedrooms, family room, living room, kitchens, bathroom used the most by the subject, other bathrooms, dining areas, basement, front door, front yard, back yard, and other locations. At the end of the 24-h period, the data collector carefully reviewed the activity diary with the parent, clarified and completed all unclear or missing information, and reviewed the subject's movements with both parent and subject to insure that the protocol was carefully followed. These reviews indicated that compliance with the experimental protocol was very good.

Area Measurements

Magnetic-field meters. Spot and long-term magnetic-field measurements were made at standardized locations with EmdexC meters (Electric Field Measurements Company, West Stockbridge, MA), which are described in detail elsewhere [Enertech, 1989a,b]. Computer programs were written for the EmdexC to implement special features of the study protocol so that the data collector could 1) display the resultant field strength without recording data, 2) record a series of 5 or a series of 60 measurements, taken over 5s or 60s, respectively, 3) record a measurement every 30s during a 24-h period (a series of 2880 measurements), or 4) continuously sample, at a rate of 1 measurement per s, the magnetic field in selected school environments (e.g., room or hall).

Stored in the EmdexC data files were sequences of individual measurements of the three vector components of magnetic flux density (B_x, B_y, and B_z, z oriented vertically). Software used to process these files computed the total rms resultant magnetic flux density,

$$B = \sqrt{B_x^2 + B_y^2 + B_z^2} \ .$$

Prior to obtaining measurements for a given residence or school, the calibration and proper functioning of EmdexC meters were checked using a small portable field source. Software was provided to the data collectors enabling them to examine the magnetic-field data from each residence or school, as soon as it was transferred from an EmdexC to a personal computer, to insure that there were no major problems with the measurements.

Normal-power spot measurements in residences. Normal-power spot (NPS) magnetic field measurements in residences were made in all rooms in which a parent estimated that the subject had spent, on the average, 15 or more minutes per day during the preceding week. Normal power conditions were achieved by turning all appliances on (or off) to simulate conditions that would exist during normal usage of a room when the child was present. NPS measurements were also made immediately outside the front door of the home and at selected outdoor yard locations.

NPS measurements were made in a room or other area at specific locations selected according to both "standardized" and "child-specific" criteria. Standardized measurements were made at the center points of rooms (but not near appliance sources), in the centers of yards, and immediately outside the front door. (All measurements were made by a meter worn by the technician at waist height.) Child-specific measurements were taken within a room or yard at one or more locations identified by a parent as places where the subject spent significant amounts of time. These locations were labeled C_1, C_2, etc., in declining order of frequency of usage. A standardized or child-specific NPS measurement consisted of five serial measurements, one per second, of the vector magnetic field at the selected location.

Low-power spot measurements in residences. Low-power spot (LPS) measurements in residences were made following a similar protocol to the NPS measurements, but with all appliances and lights throughout the home turned off or on as they would normally be configured to simulate typical night-time sleeping conditions. (Other investigators have noted that LPS conditions exclude contributions from most residential appliances and are, thus, approximate measures of the fields produced by proximate power lines and other external sources [Savitz et al., 1988; Severson et al., 1988].) LPS measurements were made at the center and C_1 locations in each room in which NPS measurements were made; measurements were not taken under LPS conditions at the front door or at outdoor locations.

Ground-current magnetic-field measurements in residences. Ground currents can be a significant source of magnetic fields in some homes [Wertheimer and Leeper, 1979; Zaffanella, 1989; Mader et al., 1990] and can arise because 1) the home itself injects current into its safety ground system and 2) current injected into the ground by other homes returns to the power system through the safety ground system of the subject home. We used the "tracer-load" technique described by Zaffanella [1989] to measure magnetic fields produced by ground currents of the first type.

A modified electric heater plugged into a kitchen circuit in each subject's residence cycled between three states: off for a duration of 12 s, on and drawing a load current of 7 amps for 6 s, and on and drawing a load of current of 12 A for 9 s. Except for homes with knob and tube wiring, the introduction of a tracer load would not affect a residence's magnetic fields unless some fraction of the load current passed through the ground system rather than through the home's own internal wiring and service drop. The presence of such ground currents would result in changes in magnetic field strength that would occur in synchrony with changes in the tracer-load current. Quantitatively, we determined a ground-current coefficient which equalled the magnetic field produced by the addition of a 1-A 115-V electrical load.

Twenty-four-hour bedroom measurements. An EmdexC meter, programmed to sample the x, y, and z components of magnetic flux density every 30 s, was placed in the subject's bedroom during the same 24-h period when the personal exposure meter was worn. (The 24-h bedroom measurement is hereafter referred to as LTB.) The specific location, either under or near the bed, where the meter was placed was a point where the field strength was found to be similar in magnitude to the level on top of the bed where the subject normally slept.

Home power consumption. The total electrical power consumed in each residence during the 24-h period that the LTB and the personal exposure data were obtained was measured by reading the home's electric power meter at the beginning and at the end of the measurement period.

School magnetic-field measurements. Magnetic-field measurements were taken in schools between April and August of 1990. Measurements were made during the day but, at the request of several school administrators, only when children were absent from the particular facilities under study. Lights and other equipment, such as heating and air conditioning systems, were turned on to simulate normal conditions when the subjects were in school.

School principals or other administrators identified the subject's primary classroom and other locations inside and immediately outside each school where children in the same grades as the subject would be expected to spend, on the average, 1 h or more per week. Measurements were obtained in these locations using a standardized approach. With an EmdexC meter continuously sampling at a rate of 1 measurement per second, a technician walked at a steady rate of about 1 pace per second, around the perimeter of each area, then across the centers of the rooms from each pair of diagonal corners. In this way a large area, such as a classroom or gymnasium, could be rapidly sampled. The data obtained in each such area were then averaged to yield one summary value.

We obtained field measurements in the following school areas: the primary classroom (defined as that classroom in which the subject spent the largest fraction of his/her time during the school year); other classrooms used by children in the same grade as the subject; common rooms used by children in several grades, such as art, music, and computer rooms and science laboratories; and in hallways, playgrounds, libraries, gymnasiums, and cafeterias.

Residential Wire Coding

Wire coding is a system for categorizing homes in relation to nearby power line configurations based on putative electric current levels, as judged by the number and types of nearby wires, and distances between them and the residence under study [Wertheimer and Leeper 1979, 1982]. Residences characterized as being very high current configuration have been linked with a significantly elevated rate of childhood leukemia [Wertheimer and Leeper, 1979; Savitz et al., 1988; London et al., 1991]. The 1982 version of the WL code classifies power line configurations into the following five categories: VHCC (very high current configuration); OHCC (ordinary high current configuration); OLCC (ordinary low current configuration); VLCC (very low current configuration); and UC (underground wiring) [Wertheimer and Leeper, 1982].

A single experienced technician made standardized drawings of all transmission, primary distribution, and secondary distribution wiring within 150 feet of each study subject's home, and classified each home using the 1982 version of the Wertheimer and Leeper code.

Methods of Analysis

Statistical methods. Magnetic fields measured across residences tend to be highly skewed, with most residential fields clustered below 0.1 μT (1 mG). However, the use of log-transformed values results in frequency distributions that are much more normal in structure. Consequently, throughout this paper, we have summarized data using both untransformed and log-transformed field values. The description of untransformed data is best done using arithmetic statistics (mean, standard deviation), whereas log-transformed data are best summarized using geometric statistics (geometric mean, geometric standard deviation). Similarly, when computing correlations between two variables (e.g., personal exposure and bedroom magnetic fields), both untransformed and log-transformed data were used.

RESULTS

Subjects and Their Activity Patterns

The ages of the 29 subjects (15 boys, 14 girls) ranged from 4 months to 8 years (mean = 5.4 years, S.D. = 2.4 years). Twenty-one percent of the subjects were aged 0–2 years, 28% were 3–5 years, and 52% were 6–9 years of age. Eleven of these children attended 10 different public schools, 8 attended 6 different private schools, and 2 attended 1 daycare center. All of the parents were high-school graduates, all had some college or vocational training, at least one spouse of 27 of 29 families was a college graduate, and at least one spouse of 22 of 29 families had some postgraduate training. The high educational level of participating families is a reflection of the fact that they were mostly recruited from the staff of research-oriented companies and institutes. Twenty percent of subjects lived in homes aged between 0 and 25 years, 40% in homes aged 26–45 years, and the remainder in homes more than 45 years old.

Table 1 summarizes the proportions of time the 29 subjects spent at or near

TABLE 1. Weekday Times Spent by Subjects at Various Locations While Wearing Personal Exposure Meters

	Time spent at location (h)			
Location	Mean	S.D.	Min	Max
All locations	**24.3**[a]	**0.9**	**22**	**27.5**
At home	**17.2**	**3.0**	**12.5**	**24.0**
Subject's bedroom	10.7	1.7	8.0	14.8
Family room	1.6	2.0	0	8.3
Living room	1.4	1.9	0	7.2
Kitchen	1.0	1.1	0	3.8
Dining room	0.5	0.7	0	2.3
Second bedroom	0.8	1.3	0	4.7
Front yard	0.3	0.5	0	2.5
Back yard	0.2	0.7	0	2.5
Other	0.7	0.7	0	2.5
Away from home[b]	**7.1**	**3.2**	**0**	**12.0**
School/daycare	4.7	2.7	0	9.1
Automobile	1.0	0.9	0	2.5
Stores	0.2	0.4	0	1.4
Other indoor locations	0.4	0.7	0	2.5
Other outdoor locations	0.7	1.3	0	6.0

[a]Although meters were worn for a nominal 24 h, the actual time was determined by when the technician returned to the home to collect the meter.

[b]Three subjects did not leave home.

home (in specific rooms or locations inside or immediately outside the residence) and away from home (at school or daycare, riding in automobiles, shopping in stores, or at other indoor and outdoor nonresidential locations) during the 24-h weekday period when personal exposure measurements were taken. On average, the subjects spent over 71% of their weekday time at their residences with 44% of the entire period spent in their bedrooms. During approximately 29% of the measurement period, the subjects were away from home, with two-thirds of this time spent at school or daycare.

Personal Exposure Measurements

Not-at-home personal exposures were measured for 26 of the 29 subjects; three subjects did not leave their homes during the study period. The distribution of TWA residential and non-residential personal-exposure levels (Fig. 1) were consistent with log normality (Shapiro-Francia test [1972]: $P = 0.53$ and 0.37 for the residential and non-residential data, respectively). In the summary statistics for measured residential, non-residential, and total (sum of residential and non-residential) personal-exposure levels shown in the upper portion of Table 2, the most striking finding is the markedly smaller variability in the not-at-home component of exposure compared with that of the residential component. This difference is statistically significantly (*F* test, $P = 0.013$). Since the log-transformed residential and total personal exposure levels were highly correlated ($r = 0.97$), the residential magnetic field exposures were the source of nearly all of the between-subjects variability in total exposure.

Normal- and Low-Power Spot Measurements

Normal-power spot (NPS) and low-power spot (LPS) measurements were log normally distributed. The means of NPS and LPS magnetic field measurements taken at the centers of rooms or yards were generally <0.2 μT (Table 2). NPS levels were, on average, no more than 20% higher than LPS measurements. The mean of children's

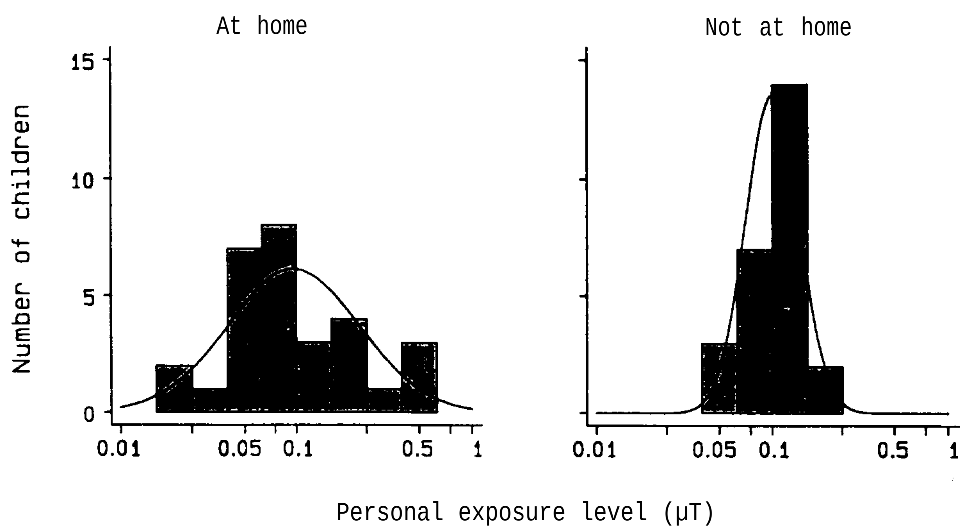

Fig. 1. Distribution of residential and non-residential personal exposure levels measured for 29 subjects. (Three subjects did not leave their homes.) Curves in figures are normal distributions with means, standard deviations, and areas set equal to values calculated from empirical data.

TABLE 2. Summary Statistics for 24-h TWA Personal Exposure Levels and 24-h Bedroom and Spot Magnetic Fields Measured in 29 Homes

	Normal power				Low power			
	Arithmetic		Geometric		Arithmetic		Geometric	
Location	Mean (μT)	S.D. (μT)	Mean (μT)	S.D.	Mean (μT)	S.D. (μT)	Mean (μT)	S.D.
Personal exposure[a]								
Residential	0.141	0.142	0.096	2.38	—[b]	—[b]	—[b]	—[b]
Non-residential	0.106	0.038	0.100	1.42	—[b]	—[b]	—[b]	—[b]
Total	0.131	0.106	0.105	1.89	—[b]	—[b]	—[b]	—[b]
24-h bedroom								
Subject's bedroom	0.131	0.107	0.099	2.10	—[b]	—[b]	—[b]	—[b]
Spot								
Subject's bedroom[c]	0.157	0.166	0.104	2.39	0.140	0.171	0.082	2.69
Family room[c]	0.116	0.116	0.085	2.13	0.107	0.131	0.067	2.50
Living room[c]	0.170	0.161	0.123	2.17	0.140	0.150	0.096	2.33
Kitchen[c]	0.151	0.128	0.115	2.08	0.126	0.114	0.095	2.07
Dining room[c]	0.173	0.159	0.131	2.02	0.126	0.123	0.096	2.00
Second bedroom[c]	0.183	0.274	0.101	2.71	0.164	0.253	0.080	3.06
Front door[d]	0.205	0.197	0.139	2.41	—[b]	—[b]	—[b]	—[b]
Front yard[c]	0.222	0.211	0.154	2.35	—[b]	—[b]	—[b]	—[b]
Back yard[c]	0.093	0.132	0.063	2.11	—[b]	—[b]	—[b]	—[b]

[a]Time-weighted-average personal exposure measured with AMEX-3D meter.
[b]No low-power data available.
[c]Measured at center of room or yard.
[d]Measured immediately outside door (measurements available for 28 homes).

bedroom NPS measurements was similar to (though slightly higher than) the mean of the 24-h TWA measurements in this room. Surprisingly, magnetic field levels in the kitchen were not notably higher than those in most of the other rooms. Field levels were highest in the front yard, although there was substantial variability in the measurements at this location.

Measurements taken at the centers of rooms were generally highly correlated with those obtained at the specific locations most frequently occupied by subjects (C_1 locations). The correlation of these measurements was lowest for the kitchen, perhaps reflecting the high concentration of appliance sources in most kitchens (Table 3). Correlations between NPS and LPS measurements within rooms were also high (Table 3). Because of the large intra-room correlation of measurements, we will primarily focus on NPS measurements in room centers in most of the subsequent parts of this paper.

One of the most important findings of this study was the high correlation of measured residential personal exposure levels with NPS (and with LPS) measurements (Table 3). Further examination of the correlation of residential personal exposure levels with spot fields in various indoor and outdoor locations revealed that spot fields measured in subjects' bedrooms and family rooms were most strongly correlated with personal exposures.

Table 4 presents correlation coefficients of log-transformed room center NPS measurements among different rooms and yard areas. Correlations between rooms were all >0.7, but correlations between rooms and yards were slightly lower.

TABLE 3. Correlation Coefficients Between Normal-Power Spot (NPS), Low-Power Spot (LPS), and Residential Personal Exposure Field Measurements*

Location	N[a]	Room center and C_1 location[b,c]	NPS and LPS[d]	Personal exposure and NPS[d]	Personal exposure and LPS[d]
Subject's bedroom	29 (29)	0.93 (0.96)	0.87 (0.94)	0.85 (0.91)	0.87 (0.92)
Family room	19 (18)	0.97 (0.98)	0.97 (0.98)	0.80 (0.78)	0.82 (0.83)
Living room	20 (18)	0.81 (0.74)	0.75 (0.83)	0.70 (0.76)	0.70 (0.78)
Kitchen	26 (24)	0.74 (0.64)	0.73 (0.76)	0.61 (0.61)	0.78 (0.82)
Dining room	14 (14)	0.92 (0.98)	0.78 (0.72)	0.42 (0.50)	0.60 (0.81)
Second bedroom	20 (20)	0.76 (0.89)	0.96 (0.99)	0.78 (0.79)	0.77 (0.79)
Front door	28[e]	—	—[f]	0.63 (0.61)	—[f]
Front yard	29 (11)	0.65 (0.51)	—[f]	0.75 (0.69)	—[f]
Back yard	29 (23)	0.97 (0.99)	—[f]	0.58 (0.62)	—[f]

*Spot measurements at room centers and child-centered (C_i) locations are included. Correlation coefficients were calculated using both log-transformed and (in parentheses) untransformed field values.

[a]Number of measurements at center of room (number of measurements at C_1 location).

[b]C_1 was location in room most frequently occupied by subject.

[c]Normal power spot measurements.

[d]Measured at center of room.

[e]Measured immediately outside front door.

[f]No low-power measurements taken at these locations.

Twenty-Four-Hour Bedroom Measurements

The TWA 24-h bedroom (LTB) means were log normally distributed. Summary statistics are given in the fourth row of Table 2. LTB fields exhibited a distinct diurnal rhythm, with a pattern similar to that observed in western Washington State [Kaune et al., 1987]. The log-transformed LTB means were found to be highly correlated with the NPS bedroom measurements (r = 0.89) and with residential personal exposure levels (r= 0.88).

One can also evaluate the correlation between any two spot measurements within a 24-h interval by regarding the LTB recordings as series of spot measurements taken 30 seconds apart. As shown in Figure 2, the correlation is very high (generally greater than 0.9) for any two measurements taken within 3 h, with correlations ranging from 0.7–0.8 for measurements differing in time from 6–24 h.

TABLE 4. Within-Home Correlations Between Log-Transformed Normal-Power Spot Magnetic Fields Measured at Centers of Rooms and in Yards of Homes of Subjects*

	Subject's bedroom	Family room	Living room	Kitchen	Dining room	Second bedroom	Front door	Front yard
Family room	0.70 (19)							
Living room	0.81 (20)	0.85 (13)						
Kitchen	0.70 (26)	0.72 (16)	0.95 (18)					
Dining room	0.78 (14)	0.86 (9)	0.95 (12)	0.90 (12)				
Second bedroom	0.89 (20)	0.77 (15)	0.85 (14)	0.72 (19)	0.73 (10)			
Front door	0.63 (28)	0.62 (18)	0.72 (20)	0.55 (25)	0.62 (14)	0.55 (19)		
Front yard	0.70 (29)	0.67 (19)	0.72 (20)	0.60 (26)	0.42 (14)	0.67 (20)	0.84 (28)	
Back yard	0.64 (20)	0.86 (19)	0.64 (20)	0.58 (26)	0.53 (14)	0.74 (20)	0.56 (28)	0.51 (29)

*Numbers of homes used to calculate coefficients indicated in parentheses.

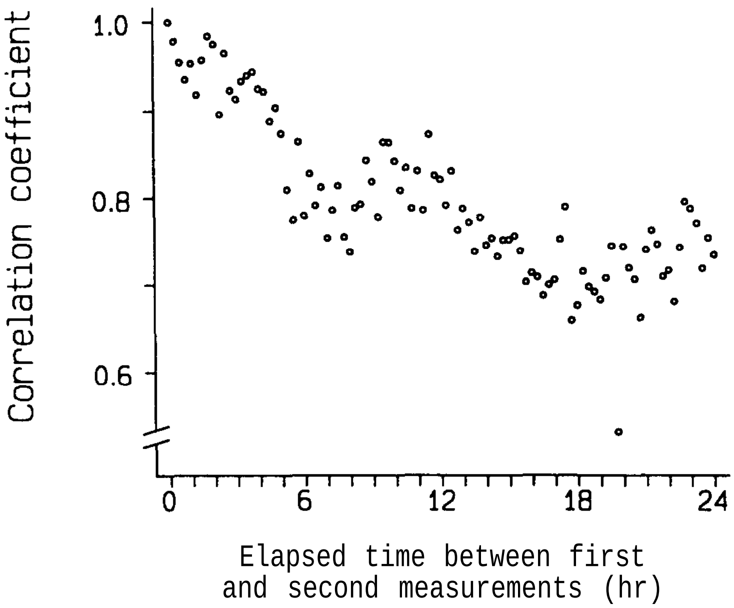

Fig. 2. Correlation between bedroom spot measurements taken at points in time separated by 0–24 h.

Home Power Consumption

Total 24-h electricity consumption was not significantly correlated with log-transformed measured personal residential exposures (r= -0.08) or log-transformed LTB mean values (r= 0.10).

Prediction of Residential Exposures

The simplest way to predict a time-weighted-average exposure level using spot and 24-h measurements is with the formula

$$B_{pred} = \left(\sum_r B_r \Delta T_r \right) / \left(\sum_r \Delta T_r \right), \quad (1)$$

where B_r is the spot or 24-h-mean field measured in the r^{th} room or yard and ΔT_r is the time spent in this room. Average values for ΔT_r were taken from Table 1, and the 24-h-mean field in the subject's bedroom and NPS measurements in the other locations were used for B_r. We tested predictions in a step-wise fashion by including in equation 1 progressively more rooms. First, only the subject's bedroom was considered in calculating the predicted value: the correlation between the log-transformed measured and predicted residential exposure levels was 0.88 (left panel in Fig. 3); that is, 77% of the variability between homes was explained by the predicted field. When the next two most frequently occupied rooms (the living and family rooms) were included, the correlation increased to 0.90 (81% of between-home variability explained). Finally, the kitchen was included, but this did not materially change the correlation between measured and predicted exposures. The right panel in Figure 3 is a scatter plot showing the relation between measured exposure levels and the prediction obtained using all four rooms. (Data for only the 23 of 29 homes that had measurements in all four rooms are presented in this figure.) Substitution of LPS for NPS measurements produced equivalent predictions of residential exposure—not surprising since these two measurements were highly correlated (Table 3).

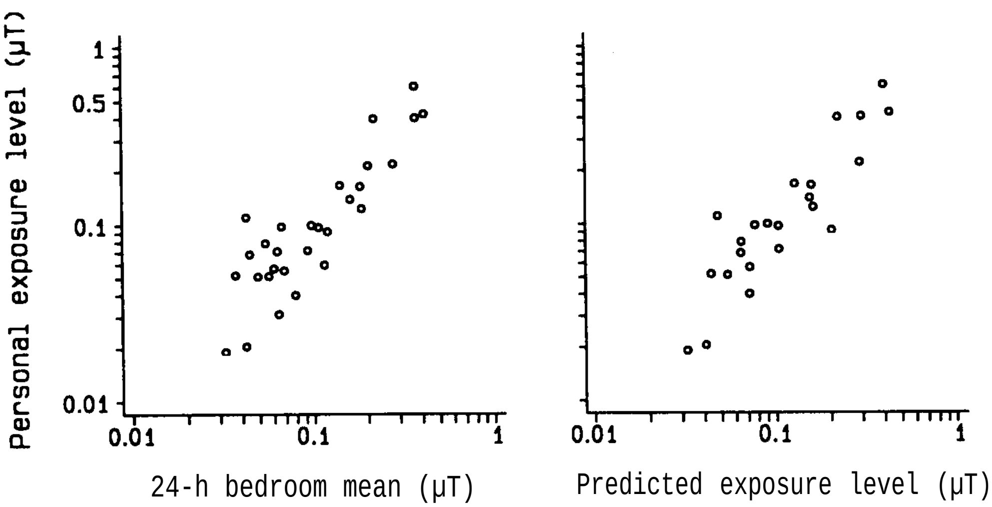

Fig. 3. Correlation of measured personal exposure levels with long-term bedroom magnetic fields **(left panel)** and exposure levels predicted using bedroom, family room, living room, and kitchen spot measurement data **(right panel)** and equation 1 in text.

Wire Codes

Each residence was classified into one of four WL wire code categories for overhead power lines (VHCC, OHCC, OLCC, VLCC). Figure 4 shows the LTB 24-h magnetic field measurements and residential personal-exposure TWA stratified by the WL categories of the subjects' residences; geometric means and standard deviations are also shown in this figure. The geometric means of the LTB and of

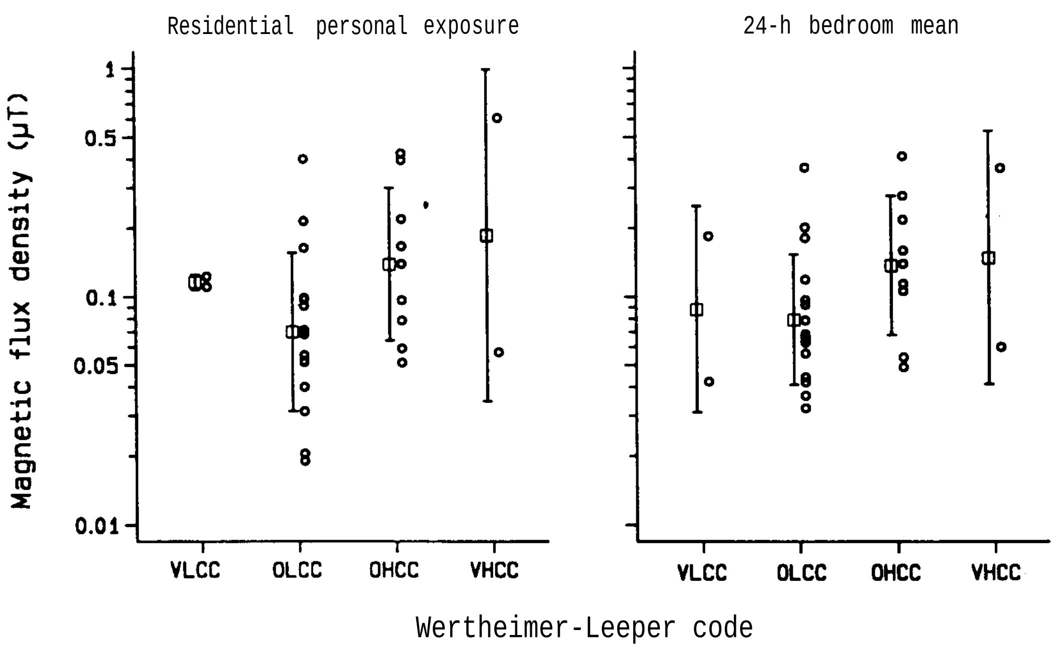

Fig. 4. Personal exposure levels **(left panel)** and 24-h bedroom means **(right panel)** measured in homes with very low-current (VLCC), ordinary low-current (OLCC), ordinary high current (OHCC), and very high-current configuration (VHCC) wire codes. Individual data points, geometric means, and geometric standard deviations are shown with circles, squares, and vertical lines, respectively.

the measured personal exposure levels were low in the two lowest WL categories (VLCC and OLCC), mid-level in the OHCC category, and were highest in the VHCC category. Due to the large variability in LTB and personal exposure level means within each wire code category, the four-level WL code only explains a small fraction (18%) of the total variability in the log-transformed data.

Ground-Current Magnetic Field Measurements

The distribution of ground-current coefficients (GCCs) measured at the centers of subjects' bedrooms was strongly skewed, with 27 of the 29 values below 0.025 µT/A (eight were consistent with 0). Ground-current coefficients measured at different locations within a room were moderately to strongly correlated (within kitchens and living rooms, $r \approx 0.6$; within subjects' bedrooms and family rooms, $r > 0.9$, respectively). On the other hand, GCCs measured in different rooms within a home were only weakly correlated ($r < 0.5$).

All studies that have examined the relation between wire codes and measured fields or personal exposures have found that a significant fraction of VLCC and OLCC homes actually have high fields [Kaune et al., 1987; Barnes et al., 1989] (Fig. 4). One possibility is that some of these homes have significant levels of ground current that account for their high fields. To explore this question, Figure 5 shows the relations between measured residential personal exposure levels and bedroom GCCs for low-current-configuration (LCC = VLCC + OLCC) and high-current-configuration (HCC = OHCC + VHCC) homes. Excluding homes with GCCs consistent with zero (i.e., £ 10^{-4}µT/A), there is a relatively strong relation between personal exposures and bedroom GCCs for LCC, but *not* HCC, homes. This result suggests that the WL code might usefully be modified to include in the HCC class homes that were LCC on the basis of external power line wiring but which had sufficiently high GCCs (e.g., bedroom GCC above the median value of 0.005 µT/A). Figure 6 shows the resulting distribution of measured residential personal exposures stratified by this modified two-level wiring code. The modified code explains 28% of

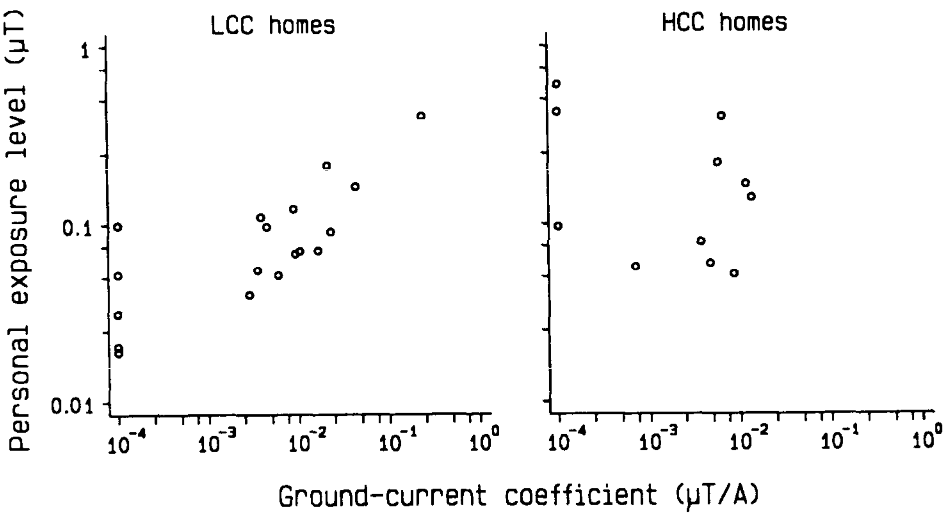

Fig. 5. Correlation between measured residential personal exposure levels and ground-current coefficients measured at centers of bedrooms of subjects living in low-current-configuration (LCC) and high-current-configuration (HCC) homes.

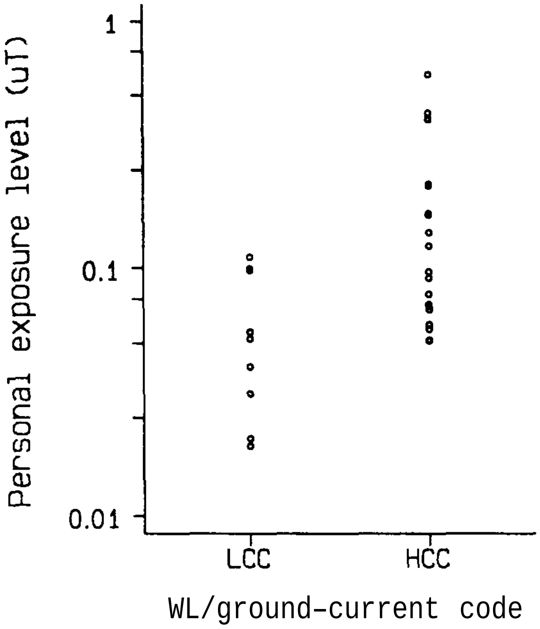

Fig. 6. Personal exposures measured in homes categorized by a modification of the Wertheimer-Leeper wire code in which homes that would be classified as LCC on the basis of external power line wiring are, instead, classified as HCC if their bedroom ground-current coefficients exceed 0.05 μT/A.

the between-house variability in log-transformed personal exposure levels compared to the 15% explained by the basic two-level WL code.

School Measurements

The average fields measured in school rooms and other school locations were more nearly log normally than normally distributed. Table 5 presents statistics summarizing the average magnetic field levels measured in various school areas. Except for the "other areas" category, the field levels measured in schools were substantially lower than the spot fields, 24-h bedroom fields, and personal exposure levels measured in residences (Table 2). Within schools, correlations between

TABLE 5. Summary Statistics for Magnetic-Field Data Obtained in Schools and Daycare Centers Attended by Subjects

		Arithmetic		Geometric	
Area	N	Mean (μT)	S.D. (μT)	Mean (μT)	S.D.
Primary classroom	19	0.054	0.020	0.052	1.4
Other classrooms	15	0.060	0.024	0.056	1.5
Hallways	20	0.099	0.050	0.087	1.7
Playgrounds	20	0.058	0.026	0.053	1.5
Libraries	16	0.050	0.016	0.048	1.4
Gymnasiums	16	0.078	0.058	0.063	1.9
Other areas[a]	17	0.123	0.096	0.093	2.2

[a]Includes 7 art rooms, 8 music rooms, 4 computer rooms, 4 bathrooms, 1 multi-purpose room, and 1 counselor's office.

various locations were, in general, low to moderate. For example, the correlation between the average fields measured in the subject's primary classroom and in other classrooms was about 0.5. Correlations of measured non-residential personal exposures with the mean magnetic field levels for various schoolrooms and other school locations were low, with the exception of "other areas" (seven were art rooms, eight music rooms, four bathrooms, four computer laboratories, a multi-purpose room, and a counselor's office) and, to a lesser extent the gymnasiums (Table 6). The mean magnetic field levels measured in the "other areas" was substantially greater than the mean measurement values obtained in other school locations (Table 5).

FINAL EXPOSURE PROTOCOL

Comparison of children's TWA 24-h personal residential and non-residential exposures with spot and 24-h measurements taken in residences and schools yields several important findings that are directly pertinent to the development of a magnetic field exposure-assessment protocol for a case-control study of childhood ALL. First, children's residential time-weighted-average (TWA) exposures to power-frequency magnetic fields were larger and considerably more variable than their non-residential TWA exposures. Second, measurements made in subjects' bedrooms were most highly correlated with residential TWA personal exposures. In addition, residential normal-power spot measurements at room centers were highly correlated with measurements taken at other room locations, as were normal-power with low-power spot residential measurements. Pairs of spot measurements (obtained in the 24-h LTB monitoring) separated in time by 0–24 h were well correlated. Ground-current magnetic-field measurements were not very useful in predicting residential TWA exposure.

In general, the geometric means of TWA personal residential exposure levels, stratified by WL wire code, were lowest in the two lowest wire codes, were higher for the OHCC code, and were highest for VHCC homes. But the residual variabilities in personal residential exposures within wire code categories were sufficiently large that the WL code could not be considered to be an effective predictor of children's contemporaneous TWA personal exposures. Most school measurements were only weakly predictive of measured non-residential TWA exposures.

Based on these results, and three other considerations, the protocol that will be presented below was selected for characterizing magnetic field exposure in homes

TABLE 6. Correlation Coefficients Between Log-Transformed (and Untransformed) School Magnetic Field Measurements and Measured Personal Exposure Levels

Area	N	Correlation with personal exposure
Primary classroom	19	0.34 (0.28)
Other classrooms	15	-0.24 (-0.27)
Hallways	20	0.40 (0.29)
Playground	20	0.42 (0.38)
Library	16	0.19 (0.17)
Gymnasium	16	0.61 (0.67)
Other	17	0.68 (0.71)

currently or previously occupied by a subject in the large CCG/NCI case-control study. These three additional considerations were:

1. Wire codes have been found to be associated with childhood leukemia in three population-based studies [Wertheimer and Leeper, 1979; Savitz et al., 1988; London et al., 1991].
2. Magnetic field measurements made under low-power conditions by Savitz et al. [1988] were weakly correlated with childhood leukemia, whereas measurements made under high-power conditions were not associated with increased occurrence of this neoplasm.
3. Because significant fractions of subjects may not provide access to their residences [Savitz et al., 1988; London et al., 1991], we decided to include a measurement just outside the front door.

The final protocol includes normal- and low-power spot magnetic-field measurements at the center of the bedroom used by the subject prior to the diagnosis or, for controls, reference date, and normal- and low-power spot magnetic-field measurements at the center of the kitchen, the center of the room (other than the child's bedroom or kitchen) most frequently used by subject, and immediately outside the front door. In addition, the protocol includes a 24-h magnetic-field recording at a point in the bedroom used prior to diagnosis that is determined to have a magnetic field level similar in magnitude to that measured at a location on the surface of subject's bed where the subject usually slept. Finally, the residence will be diagrammed and coded using the five-category WL coding scheme.

The latency period between magnetic field exposures and possible onset of childhood ALL is not known, so it is not possible to identify a time prior to the diagnosis/referent date when exposure was most important. Savitz et al. [1988] reported the strongest association between cancer incidence in children and the wire codes of homes occupied 2 years prior to the diagnosis/referent date. Laboratory data indicate that magnetic fields may act as a cancer promoter rather than as a cancer initiator [Adey, 1990]. For these reasons, as well as because of concerns about the use of contemporaneous magnetic-field measurements to assess exposures that occurred long in the past, we decided to concentrate on the 5-year period preceding the diagnosis/reference date or, for subjects with ages less than 4 years and 3 months, the period extending from the date of conception to the diagnosis/referent date. In selecting this study period, it seemed reasonable to identify an interval which would include the child's lifetime from conception to diagnosis/reference date for the 40% of childhood ALL cases that are estimated to be <5 years old at diagnosis, and a reasonable fraction of the interval prior to diagnosis/reference date for the remainder of subjects.

No measurements at the schools currently or previously attended by subjects are included in the protocol because non-residential exposures were only weakly associated with measured *total* personal exposure. (Had we measured weekend as well as weekday exposures, this association presumably would have been even weaker.) To further clarify this point, consider that the total daily exposure level, B, is a weighted sum of the residential, B_R, and non-residential, B_N, exposure levels: $B = f_R B_R + f_N B_N$ where f_R and f_N are the fractions of time spent at and away from home, respectively. Denote the variabilities in the residential and nonresidential components as Var $(B_R) = \sigma_R^2$ and Var $(B_N) = \sigma_N^2$, respectively. Then, the variability in the total daily exposure level is Var $(B) = f_R^2 \sigma_R^2 + f_N^2 \sigma_N^2$. The covariance between the total and residential exposure levels is Cov $(B,B_R) = f_R \sigma_R^2$. Consequently, the correlation between the residential and total exposure levels is

$$\rho(B, B_R) = \frac{\mathrm{Cov}(B, B_R)}{\sqrt{\mathrm{Var}(B)\mathrm{Var}(B_R)}} = \left[1 + \left(\frac{f_N}{f_R}\right)^2 \left(\frac{\sigma_N}{\sigma_R}\right)^2\right]^{-1/2}. \tag{2}$$

In the dosimetry study, $f_N = 0.29$, $f_R = 0.71$, $\sigma_N = 0.04$ µT, and $\sigma_R = 0.14$ µT (Tables 1, 2), so equation 2 predicts $\rho(B,B_R) = 0.99$. (The value derived directly from the data was 0.98.)

It is possible that our finding of a reduced non-residential exposure variability will not generalize to larger samples, to other geographical areas in the US, or to exposures measured during seasons other than spring and summer. (For example, a recent study in Canada found similar variabilities in childrens' residential and non-residential exposures [Donnelly and Agnew, 1991].) However, because young children spend most of their time at home, it is likely that residential and total exposure levels will be strongly correlated in most or all geographic areas within the US. (For example, if $\sigma_D \approx \sigma_N$, σ_R would still be quite large at about 0.93.) Thus, we concluded that the additional effort required to characterize school exposures was not warranted.

DISCUSSION

Currently, an important unresolved issue is to determine why the WL coding scheme for residences appears to be significantly associated with childhood cancer, particularly leukemia risk, whereas magnetic field measurements are not [Savitz et al., 1988; London et al., 1991]. One hypothesis is that the biologically important factor is some characteristic of the residential magnetic field neither measured nor predicted by spot and 24-h magnetic-field averages, but strongly associated with wiring configuration. Magnetic field exposures that have been considered in this context include exposure to peak magnetic fields, magnetic fields above a minimum threshold, intermittency (i.e., occasional or frequent changes in magnetic-field strength), harmonics, direction of the field vector, and magnetic-field transients (i.e., magnetic-field perturbations lasting for periods of time small in comparison to the length of a 60-Hz cycle). Presumably, measurements of the appropriate factor should be substantially more strongly associated with wiring codes than would TWA exposure measures. We used the 24-h bedroom magnetic-field recordings taken in the study to examine correlations between a number of these exposure measures and wire codes, but we found no evidence of any magnetic-field or intermittence measure that was substantially more strongly correlated with wire codes than with the arithmetic mean field.

Another possibility is that the observed association between wire codes and childhood leukemia or central nervous system cancer is truly the result of a confounding exposure—that is, an exposure that is associated with the wire codes and cancer but is unrelated to magnetic-field exposure. One *possibility* for such a confounding factor could be the pesticides or herbicides sprayed on the wooden poles supporting power lines or on the right-of-ways underneath most transmission lines.

The results presented in this paper are based on measurements during two seasons (spring only for homes, both spring and summer for schools) in 29 homes in one geographical area and involving families of upper socioeconomic status. (The limitations of sample size are even more severe in the school data.) Consequently, conclusions drawn from the work must be regarded as tentative. Furthermore, this work does not address the question of how effective magnetic-field measurements taken in the present are as estimators of exposures that occurred months or years earlier. In this context, the only relevant data that we are aware of come from two studies. In the first, Dovan, Kaune, and Savitz [1993] made spot measurements during 1990 in 81 Denver homes that had previously been spot-measured by Savitz et al., [1988] in 1985. The correlation between these two sets of (log-transformed) measurements was about 0.7, providing some evidence for the usefulness of contemporaneous measurements as estimators of historical exposures. On the other hand, Feychting and Ahlbom [1992] found that the electrical loads carried by Swedish transmission lines had changed so much over time that contemporaneous measurements were at best only weak predictors of the historical exposures of people living near these lines.

To further evaluate possible geographic, seasonal, or age effects on magnetic-field exposures, we are currently obtaining personal exposure measurements on a sample of 60 control subjects aged 0–14 from the NCI-CCG study. We have also recently initiated a separate pilot study focusing on possible seasonal changes in residential magnetic fields.

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