Bioelectromagnetics 22:294–305 (2001)

Static Magnetic Field Measurements in Residences in Relation to Resonance Hypotheses of Interactions Between Power-Frequency Magnetic Fields and Humans

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Bowman et al. used epidemiologic data to test a model in which subjects were classified as being "in-resonance" or "not-in-resonance" for 60-Hz magnetic-field exposures depending on single static magnetic-field measurements at the centers of their bedrooms. A second paper by Swanson concluded that a single static magnetic-field measurement is insufficient to meaningfully characterize a residential environment. The main objective of this study was to investigate exposure-related questions raised by these two papers in two U.S. data sets, one containing single spot measurements of static magnetic fields at two locations in homes located in eight states, and the other repeated spot measurements (seven times during the course of one year) of the static magnetic fields at the centers of bedrooms and family rooms and on the surfaces of beds in 51 single-family homes in two metropolitan areas. Using Bowman's criterion, bedrooms were first classified as being in-resonance or not-in-resonance based on the average of repeated measurements of the static magnetic field measured on the bed where the presumed important exposure actually occurred. Bedrooms were then classified a second time using single spot measurements taken at the centers of bedrooms, centers of family rooms, or on the surfaces of beds, as would be done in the typical epidemiologic study. The kappa statistics characterizing the degree of concordance between the first (on-bed averages) and second (spot measurements) methods of assessing resonance status were 0.44, 0.33, and 0.67, respectively. This level of misclassification could significantly affect the results of studies involving the determination of resonance status. Bioelectromagnetics 22:294–305, 2001. © 2001 Wiley-Liss, Inc.

Key words: DC magnetic fields; resonance mechanisms; exposure assessment; geomagnetic field; misclassification; epidemiology

INTRODUCTION

Bowman et al. [1995] used epidemiological data from a study of childhood leukemia and residential magnetic-field exposure [London et al., 1991] to test the hypothesis that subjects classified as "in-resonance," because the static magnetic field in their bedrooms fell in one of the two bands 33.4–42.6 μT and 46.0–55.2 μT, would exhibit a higher risk of developing leukemia with increasing levels of 60-Hz magnetic fields than would subjects who were classified "not-in-resonance." Bowman's method for classifying resonance status was based on laboratory data indicating that the efflux of calcium from chick embryo brain tissue was increased by exposure to ac magnetic fields only if the strength of the static magnetic field had certain values [Blackman et al., 1985, 1988]. Bowman et al. [1995] assessed resonance status in an existing data set [London et al., 1991] using single static magnetic field measurements taken at the centers of bedrooms in which children slept and found a statistically significant trend towards increasing leukemia risk with increasing exposure to 60-Hz

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Received for review 23 September 1999; Final revision received 15 June 2000

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magnetic-fields in the in-resonance group that was not present in the not-in-resonance group.

A methodological study [Swanson, 1994] measured static magnetic fields in one location outside and six locations (center and four corners of the living room and next to bed in, usually, a child's bedroom) inside 55 homes located in southwest England and found that the variability of the magnetic fields measured within a typical home was greater than the variability between homes. Based on this and other findings, the author concluded that "... it is not meaningful to categorize homes by a single value of the static field."

Swanson's results suggest that Bowman et al.'s [1995] conclusions, which were based on classification of a subject's resonance status using a single static magnetic-field measurement, should be evaluated further. The primary purpose of this paper is to examine Swanson's conclusion in the context of Bowman's work with two sets of data collected in the United States as part of the National Cancer Institute/Children's Cancer Group study of residential magnetic-field exposure and childhood leukemia [Linet et al., 1997]. A secondary purpose is to examine the relation between measured static magnetic fields in residences and geomagnetic fields (i.e., the static magnetic field produced by the earth) for the same areas.

MATERIALS AND METHODS

The data on which this paper is based came from two field studies. Each of these studies is briefly described in the next two sections.

NCI/CCG Childhood Leukemia Study

Overview In 1989 the Children's Cancer Group (CCG) initiated data collection by telephone interview for a large, nationwide, comprehensive case-control study of acute lymphoblastic leukemia in children and a variety of risk factors. Soon after this study was started, it was expanded to include additional investigation of residential power-frequency magnetic fields (MF), radon, and selected other environmental exposures during visits to current and former homes inhabited by a subset of participants residing predominantly within nine mid-western and mid-Atlantic states. The magnetic-field component of the study will be referred to as the "NCI/CCG CL Study."

Subjects The NCI/CCG CL Study included case children under age 15 newly diagnosed with acute lymphoblastic leukemia during 1989–1993 and residing at diagnosis in Pennsylvania, Ohio, Michigan, Minnesota, Illinois, New Jersey, Iowa, Indiana, and Wisconsin [Kleinerman et al., 1997]. All eligible cases were treated by pediatric oncologists affiliated with hospitals participating in clinical trials carried out by the CCG. Controls were selected by random digit dialing and were individually matched to cases on age, race, and the first eight of the ten-digit telephone number. For eligible subjects under 5 yr of age, the NCI/CCG investigators attempted to obtain measurements in all homes resided in since conception for at least six months, provided that these home accounted for at least 70% of his or her life. For subjects aged five and older, the NCI/CCG investigators measured up to two homes that were resided in for at least 70% of the five years prior to the reference date (i.e., date of diagnosis for cases, date of diagnosis of the matched case for the corresponding control).

For the purposes of this paper, we restricted our attention to the control subjects of the NCI/CCG CL Study because they were the best sample of the general population.

Data collection As part of the MF measurements collected in homes occupied or previously occupied by subjects, the static magnetic field was measured at the centers of family rooms and subjects' bedrooms using a fluxgate magnetometer (described below). (See Kleinerman et al. [1997] and Linet et al. [1997] for more detailed descriptions of the NCI/CCG CL Study protocol.)

NCI Seasonal Variability Study

Overview Since the NCI/CCG CL Study collected MF data during only one 24-h period, there was concern that residential magnetic fields might vary significantly during the course of a year, especially between seasons. To investigate this, a smaller methodological study, known as the NCI Seasonal Variability (SV) Study [Banks, 1997], was undertaken in which a total of seven repeated sets of comprehensive residential measurements, taken nominally every two months during a 12-month period, were made in 51 single-family or duplex homes located in the Minneapolis-St. Paul and Detroit metropolitan areas. Hereafter, this study will be referred to as the "NCI SV Study."

Subjects The original plan was to draw subjects from the population of controls recruited for the NCI/CCG CL Study. However, it soon became apparent that this method would not yield a sufficient number to meet the NCI SV Study schedule, so additional subjects were recruited from children aged

0–14 yr who had been identified by the CCG as potentially eligible control subjects, but were not ultimately selected for the study. Subjects were selected from this group for the NCI SV Study if they resided in the Minneapolis-St. Paul or Detroit metropolitan areas and satisfied a frequency-matching age group criteria. Ultimately, 18 of the NCI SV subjects were control participants in the NCI/CCG CL Study and 33 were specially recruited for the NCI SV Study. Twenty-four subjects lived in the Minneapolis-St. Paul and 27 lived in the Detroit metropolitan areas.

Data collection Each residence in the NCI SV Study was visited a nominal seven times for static magnetic-field measurements, with each visit following the preceding one by an average of 61 days (standard deviation = 7 days). During each visit, the entire magnetic-field exposure-assessment protocol used in the NCI/CCG CL Study, which included static magnetic-field measurements at the centers of bedrooms and family rooms, was repeated. In addition, to provide more information about the spatial variability of the static magnetic field near the bed used by each subject, an additional static magnetic-field measurement was made 5 cm above the bed's surface at the location that would be occupied by the middle of the subject's torso when sleeping.

Fluxgate Magnetometer

Static magnetic-field measurements were made in both the NCI/CCG CL and NCI SV studies using a commercial fluxgate magnetometer (FGM-3D1, Walker Scientific). To facilitate the accurate measurement of the vector components of static flux density, we provided each technician with a plexiglas fixture, normally mounted on three legs at a height of 1 m above the floor. The fixture had three slots machined at right angles to position the probe of the magnetometer in three orthogonal directions, two horizontal and one vertical. These slots were placed so that the center of the probe occupied the same approximate point in space for all three orientations. For measurements on the surfaces of beds, the plexiglas fixture, with its legs removed, was set directly on the bed.

Fluxgate magnetometers used in the study underwent a primary calibration on average every 264 days. This calibration was performed in a 44 cm long, 9.4 cm diameter solenoid which was oriented with its axis perpendicular to the ambient static magnetic field produced by the earth. The absolute accuracy of this calibration was $\pm 1\%$. All fluxgate magnetometers passed these periodic calibration tests. The average deviation between the measured and calibration magnetic fields was -0.51%. In addition, field technicians checked their magnetometers for proper functioning before each use in a residence by measuring the static magnetic fields at standardized locations in the technicians' own residences.

Characterization of Static Magnetic Fields

The raw static magnetic-field data obtained using the fluxgate magnetometers and measurement fixtures described above were the *x, y,* and *z* components of the field under study. The measurement fixture was always oriented so that the *z* component was vertical. The horizontal axes were not oriented in any standardized way. The static magnetic field was characterized by its magnitude, B, and inclination angle, θ (i.e., angle between the static magnetic field and the horizontal plane) calculated as follows:

$$B = \sqrt{B_x^2 + B_y^2 + B_z^2}, \qquad \tan\theta = B_z/\sqrt{B_x^2 + B_y^2}.$$

Geomagnetic Field

The major source of the static magnetic field measured in this study was the earth. The geomagnetic field produced by the earth has a secular component that varies very slowly on a time scale of many years, a small diurnal component that varies in a regular way during the course of every 24 h day, and an erratic component associated with magnetic storms which are, in turn, related to solar activity. We obtained a computer program from the National Geophysical Data Center [NGDC, 1990] to calculate the magnitude and inclination angle of the secular component of the geomagnetic field at any selected location on the surface of the earth.

We located on a map the major CCG affiliated medical centers that participated in the NCI/CCG CL study [Kleinerman et al., 1997]. If there was only one participating center in a state, as there was in Iowa, Illinois, Indiana, Michigan, and New Jersey, we selected the center of the geographical area we estimated would be served by the medical center. For the other states with multiple CCG affiliated hospitals, we selected a geographical location located approximately midway among the facilities. We then calculated the magnitudes and inclination angles of the geomagnetic fields at each of these selected locations using the computer program described above.

Analytical and Statistical Methods

Distribution of static magnetic field data The distributions of the static magnetic fields measured in the NCI/CCG CL and NCI SV Studies were examined

graphically using histograms. The normality of these distributions was assessed using the Shapiro–Wilk test [1965].

Stability of static magnetic field data The stability (i.e., repeatability) of a sequence of repeated static magnetic-field measurements obtained in the NCI SV Study was assessed by calculating the coefficient of variation of the sequence (i.e., standard deviation divided by mean).

Variation of static magnetic field data across states Since the static magnetic-field data were not precisely normally distributed, the nonparametric Kruskal–Wallis test [Sokal and Rohlf, 1995] was used to determine whether the data obtained in the NCI/CCG CL Study varied across states. Of course, some variation would be expected because the geomagnetic field produced by the earth varies with location on the surface of earth. To determine if the state by state variation present in our data actually reflected the expected geographical variation in the geomagnetic field, we compared the measured data against the calculated geomagnetic field for each state.

Static magnetic fields in different types of residential structures Homes occupied by subjects of the NCI/CCG CL Study were classified as apartments, duplexes, single-family dwellings, row houses, and mobile homes. We tested for differences in the static magnetic fields measured in these types of structures with the Kruskal–Wallis test [Sokal and Rohlf, 1995]. If a home's structural type had no effect on the static magnetic field inside of it, and this field was predominantly due to the geomagnetic field of the earth, we would expect, on average, that the measured field B_M, would be equal to the geomagnetic field, B_G. Thus, the parameter $\alpha_h = -(B_M - B_G)/B_G$, averaged over all homes of structure type h, measures the effect of type of home on the static magnetic field. Note that a positive value of α_h indicates that the measured field was less than the geomagnetic field, which can be interpreted as an attenuation of the geomagnetic field by the structure. Thus, α_h will be referred to as an attenuation factor. Summary attenuation factors for each type of residential structure were characterized by computing the means and standard deviations of the attenuation factors determined for each home of the respective type.

Relationship between static magnetic fields measured at different locations in a home The relationship between the static magnetic fields measured at different locations within the study homes was assessed graphically by constructing scatter plots and quantitatively by calculating Spearman (rank) correlation coefficients [Sokal and Rohlf, 1995].

Classification of residential resonance status according to Bowman's hypothesis Bowman et al. [1995] classified the resonance status of a subject using a *single* measurement of the static magnetic field at the center of their bedroom. In the NCI SV Study, we made N (usually 7) sets of spot static magnetic field measurements during the course of one year in each home, at the center of the bedroom, the center of the family room, and on the surface of the subject's bed. To simulate the single spot measurement used by Bowman, we randomly selected a single center-of-bedroom measurement from each sequence of N measurements. In addition, we randomly selected one spot measurement for the center-of-family room and surface-of-bed locations. These three randomly selected spot measurements will be referred to as "single visit proxy static magnetic fields."

Children spend about 10.5 h per day in their bedrooms [Kaune et al., 1994; Friedman et al., 1996]. Consequently, since the preponderance of exposure time in a bedroom occurs while a child is in bed, we will regard this exposure as, likely, the most etiologically relevant for epidemiologic purposes. We estimated this exposure field, which hereafter will be referred to as the "gold standard on-bed static magnetic field," as follows: For comparisons with single-visit proxy static magnetic fields measured at the centers of bedrooms and family rooms, all repeated measurements on the surface of the bed were averaged to form the gold-standard on-bed static magnetic field. However, for comparisons with the on-bed single visit proxy static magnetic field, all repeated measurements except the one randomly selected to be the single visit proxy static magnetic field were included in the average. In all cases, we computed these averages only if there were available a minimum of three repeated measurements.

The relationship between the gold standard on-bed static magnetic field and a single visit proxy static magnetic-field measurement was first assessed with Spearman (rank) correlation coefficients [Sokal and Rohlf, 1995]. We then assigned gold standard resonance status following Bowman's hypothesis that a subject was in-resonance if the gold standard on-bed static magnetic field lay in the interval 33.4–42.6 μT or in the interval 46.0–55.2 μT [Bowman et al., 1995]. We next assigned a single visit proxy resonance status, as would be obtained in the typical epidemiological study and as was used by Bowman et al. [1995], by using either the single visit proxy on-bed, bedroom, or

family-room static magnetic field measurement. The relationship between single-visit proxy and gold standard resonance status (as defined earlier in this paragraph) was assessed in 2×2 tables and was characterized quantitatively using the kappa statistic [Fleiss, 1981] and by calculating sensitivity, specificity, and positive and negative predictive values [Rothman and Greenland, 1998]. The kappa statistic is a measure of the agreement between two categorical variables in excess of that due to chance alone. Thus, $\kappa = 0$ corresponds to agreement at the level expected by chance whereas $\kappa = 1$ means perfect agreement. Sensitivity is the probability that a home truly in resonance will be classified so (using a single visit proxy static magnetic field measurement), specificity is the probability that a home out of resonance will be classified so, a positive predictive value is the probability that a home classified as in resonance is truly so, and the negative predictive value is the probability that a home classified not-in-resonance is truly so.

RESULTS

Sampling Statistics

NCI/CCG Childhood Leukemia Study Table 1 lists by state the number of NCI/CCG CL Study homes, inhabited or previously inhabited by control subjects, in which valid ac and static magnetic field data were obtained. Valid static magnetic field measurements were obtained in the family rooms of the 697 homes listed in Table 1. Bedroom measurements were obtained in all but one home in New Jersey and one in Ohio.

NCI Seasonal Variability Study The NCI SV Study included 51 homes. While the protocol called for seven sets of static magnetic field measurements in each home, this goal was not always achieved because of logistical problems (e.g., family illness, vacations, families moving from study homes, scheduling difficulties). Ultimately, we obtained an average of 6.8 (standard deviation = 0.4) repeated measurements at the centers of bedroom of subjects, 6.8 (0.4) at the centers of the family rooms, and 5.5 (1.8) on the surfaces of subjects' beds. The lower number of measurements obtained on the surfaces of beds resulted mainly from the decision, made shortly after the beginning of the SV study, to add on-bed measurements to the protocol. Four homes had fewer than 3 repeated on-bed measurements and five had just 3 measurements.

TABLE 1. Numbers of NCI/CCG Childhood Leukemia Study Control Homes Included in the Data Set Used in This Paper

	Number of homes with valid static field measurements in:	
State	Bedroom	Family room
Iowa	53	53
Illinois	68	68
Indiana	43	43
Michigan	108	108
Minnesota	99	99
New Jersey	67	68
Ohio	122	123
Pennsylvania	135	135
Total	695 [a]	697

[a]Two bedroom measurements were not made, one because of the presence of an aggressive dog, the other because of data collector error.

Summary of Static Magnetic-Field Measurements

Figure 1 shows the frequency distributions of the static magnetic fields measured at the centers of

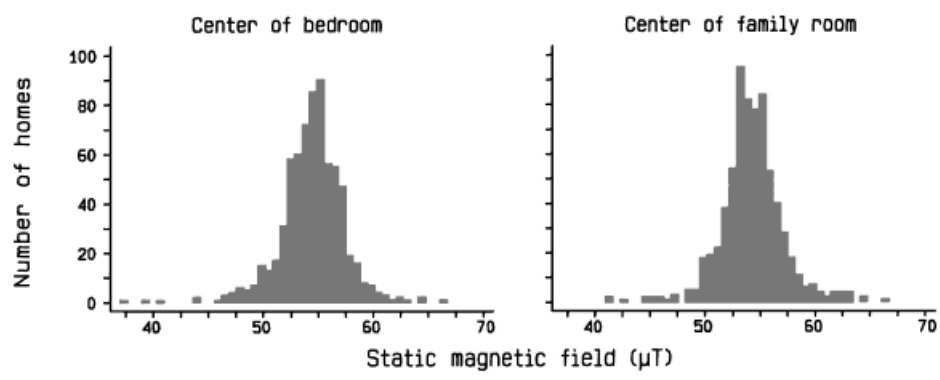

Fig. 1. Histograms showing distribution of static magnetic fields measured in 695 homes inhabited by control subjects from NCI/CCG Childhood Leukemia Study. (One center-of-bedroom measurement of 26.9 μT is not included.)

children's bedrooms and the family rooms of the homes occupied or previously occupied by control subjects of the NCI/CCG CL Study. While the data approximate a normal distribution, they actually differ in detail ($P < 0.0001$) because the tails of the distribution contain too few data points. The mean strength of the magnetic fields measured in the centers of bedrooms and centers of family rooms were 54.2 and 54.4 μT, respectively; the corresponding standard deviations were 3.0 and 2.8 μT.

Histograms showing the distributions of the mean values of each of the series of repeated measurements made at the centers of the bedrooms, on the surfaces of the beds, and at the centers of the family rooms of the 51 homes included in the NCI SV Study were similar to those in Figure 1, except that the distribution of the surface-of-bed data was broader. Mean values for these distributions were 55.9, 54.7, and 54.9 μT, respectively. The standard deviation of the surface-of-bed data (4.8 μT) was larger than for the center-of-bedroom (2.0 μT) and center-of-family room (2.5 μT) data.

Stability of Static Magnetic-Field Measurements

To quantify stability (i.e., repeatability), we calculated coefficients of variation (CV) for each sequence of repeated static magnetic-field measurements made at the three standard locations in each home enrolled in the NCI SV Study. Figure 2 presents histograms of these coefficients for the magnitudes (upper row of graphs) and inclination angles of the static magnetic field. The averages (and standard deviations) of the field-magnitude CV data obtained at the centers of bedrooms, on the surfaces of beds, and at the centers of family rooms were 0.014 (0.013), 0.074 (0.082), and 0.012 (0.007), respectively. The comparable numbers for the inclination-angle data were 0.019 (0.010), 0.054 (0.037), and 0.017 (0.009), respectively. The CVs for the measurements at the centers of rooms were quite small, indicating these quantities were quite stable over the year-long duration of the project. The CVs for the on-bed data were markedly higher, indicating that these quantities exhibited considerably larger variation between measurements. Since the static magnetic field of the earth is quite stable over time, we believe the decrease in stability (i.e., repeatability) in the on-bed measurements reflects increased spatial variability associated with ferromagnetic materials in beds and small variations in the position where the technician placed the meter during each of the seven visits to each home.

Comparison of Static Magnetic Fields Measured in Different States

The static magnetic fields measured at the centers of bedrooms and family rooms differed by state ($P < 10^{-4}$, Kruskal–Wallis test). Figure 3 compares the means and standard errors of the magnitudes and inclination angles measured in each of the eight states listed in Table 1 to the calculated geomagnetic data. These figures show that state-by-state variations in the measured static magnetic field data mimic almost exactly the state-by-state variation in the calculated geomagnetic field data.

Interestingly, while the measured and calculated inclination angles are overlapping, the magnitudes of the measured bedroom and family room static magnetic fields are consistently slightly smaller than

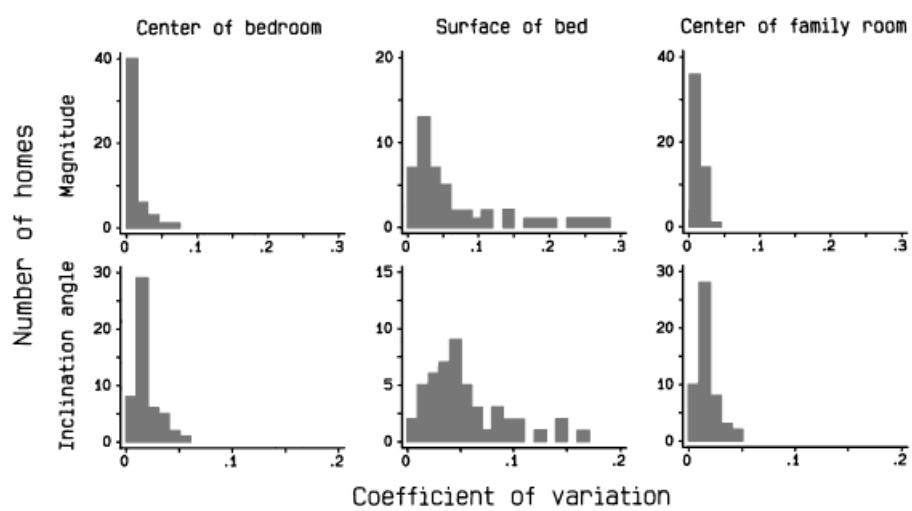

Fig. 2. Histograms showing distributions of coefficient of variations of repeated series of measurements of magnitudes (first row of graphs) and inclination angles of static magnetic fields at three locations in 51 homes of NCI Seasonal Variability Study.

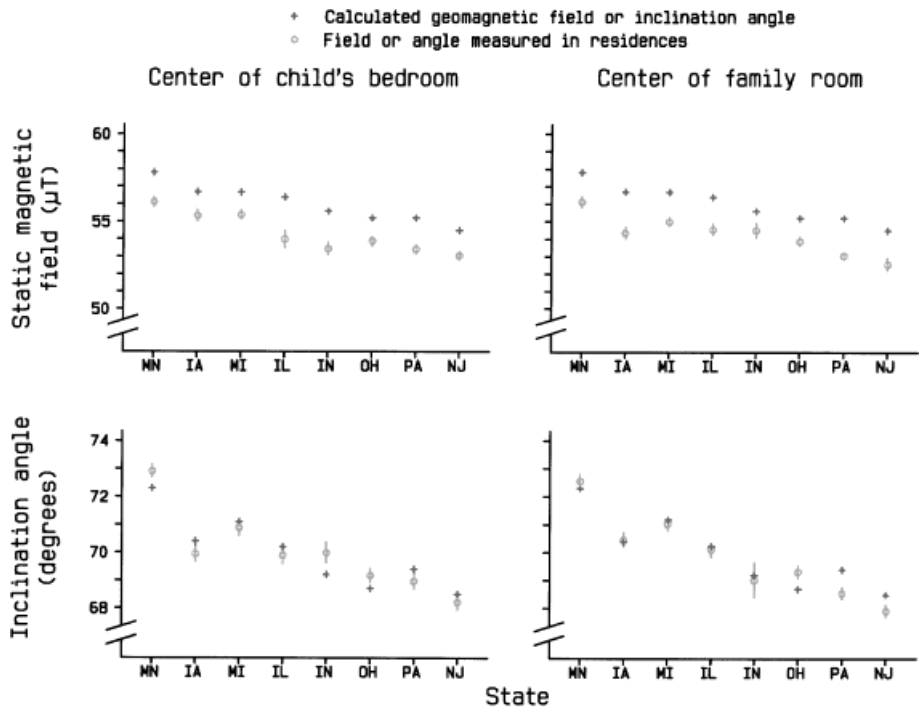

Fig. 3. Comparison of magnitudes and inclination angles of calculated geomagnetic fields and averages of static fields measured in centers of bedrooms and family rooms of homes located in eight states. Error bars extend vertically ± 1 standard error from measured mean fields.

the magnitudes of the calculated geomagnetic fields. (As indicated previously, the absolute calibration of the magnetometers used to measure these fields was accurate to $\pm 1\%$, so the differences between measured and calculated magnitudes displayed in Figure 3 are not due to measurement error.)

Comparison of Static Magnetic Fields Measured in Different Types of Residences

The magnitudes of the measured static magnetic fields differed by type of home ($P < 10^{-5}$ for centers of bedrooms, $P = 0.0002$ for centers of family rooms, Kruskal–Wallis test). We calculated the attenuation factor α_h for each type of residential structure to characterize its effect on the geomagnetic field. (α_h is the fractional difference between the two curves shown in the upper two graphs in Figure 3.) Table 2 lists the means and standard errors of α_h for each type of residence.

The mean static magnetic field attenuation factor for children's bedrooms of single family homes was about 2.5%. Similar values were obtained in duplexes and row houses, which have vertical heights similar to those of single family homes. There was no measurable statistical difference between these groups ($P = 0.77$, Kruskal–Wallis test). This collective group, however, had less attenuation than did either apartments (5.1%, $P = 0.00014$) or mobile homes (7.6%, $P < 10^{-4}$). Attenuation in apartments was not significantly different from that in mobile homes

TABLE 2. Relation Between Residence Type and Static Magnetic-field Attenuation

		Attenuation ± standard error	
Type of home	Number	Center of child's bedroom	Center of family room
Single family	560	0.025 ± 0.002	0.027 ± 0.002
Duplex	32	0.018 ± 0.009	0.030 ± 0.007
Row house	18	0.029 ± 0.013	0.055 ± 0.007
Unit in apartment building	53	0.051 ± 0.008	0.049 ± 0.006
Mobile home	34	0.076 ± 0.015	0.061 ± 0.014

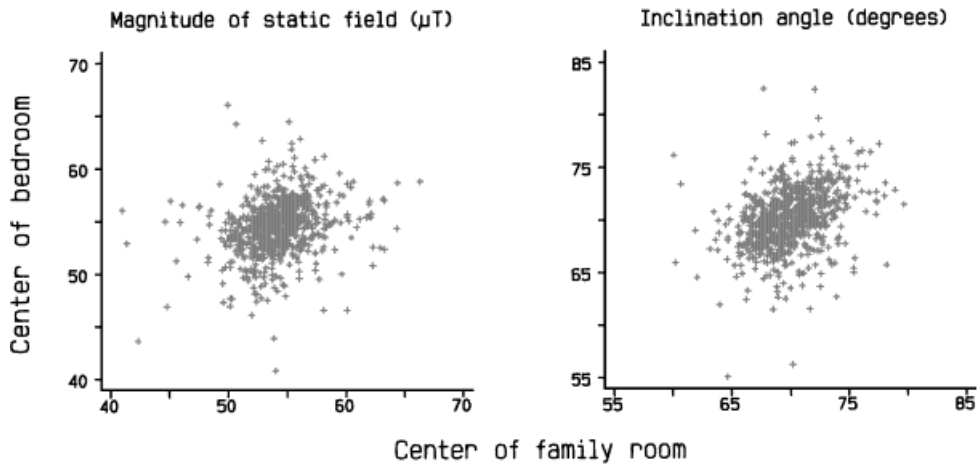

Fig. 4. Scatterplots illustrating relations between magnitudes and inclination angles of static magnetic fields measured at centers of bedrooms and family rooms in 695 residences inhabited by control subjects of the NCI/CCG Childhood Leukemia Study.

($P = 0.13$). This pattern was repeated when the family room data were analyzed.

Correlation Between Static Magnetic Fields Measured in Different Residential Locations

Figure 4 presents scatterplots comparing the magnitudes and inclination angles of the static magnetic fields measured at the centers of bedrooms and at the centers of family rooms in 695 residences inhabited by control subjects of the NCI/CCG CL Study. The Spearman correlation coefficients characterizing these relations are 0.33 and 0.39 for the field-magnitude and inclination-angle data, respectively. While both are significantly different from zero ($P < 0.0001$), the association between static magnetic field parameters measured in bedrooms and family rooms was not strong.

Figure 5 presents scatterplots illustrating the relations between the magnitudes of gold-standard on-bed static magnetic fields (defined as the averages of all repeated static-field measurements taken on the surfaces of subjects' beds) and single visit proxy static magnetic fields measured at the centers of bedrooms, on the surfaces of beds, and at the centers of family rooms. The Spearman correlation coefficients characterizing these relations are 0.41, 0.67, and 0.44, respectively. All are significantly different from 0 at the 0.01 or better confidence level. The Spearman correlation between single visit proxy spot magnetic field measurements made in the bedrooms and family rooms was 0.28 ($P = 0.055$, data not shown) and between a single visit proxy static magnetic field measurement made in the family room and on the surface of the bed 0.21 ($P = 0.18$, data not shown).

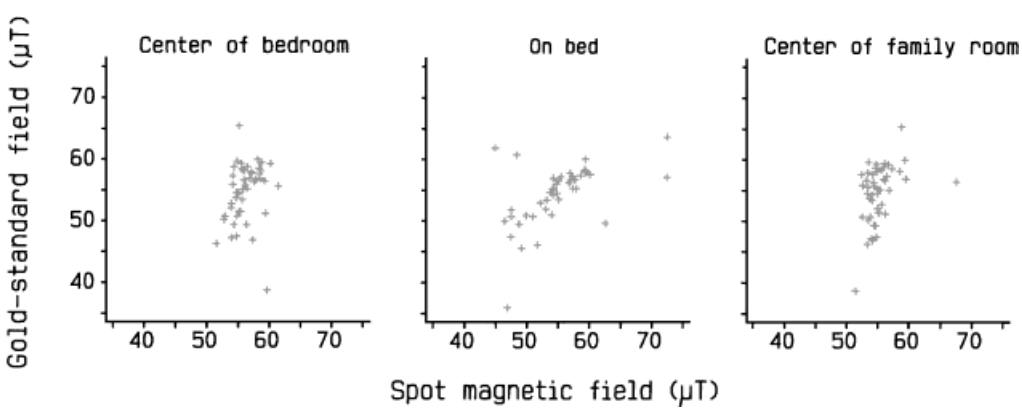

Fig. 5. Scatterplots illustrating relations between magnitudes of single visit proxy spot and gold standard on-bed magnetic fields measured in 51 residences of subjects enrolled in NCI Seasonal Variability Study.

TABLE 3. Associations Between Resonance Status[a] Assessed Using Gold-Standard On-Bed Static Magnetic Fields, and Resonance Status Assessed Using a Single-Visit Proxy Spot Measurement. The Upper Part of the Table Presents Cross Tabulations Between These Two Variables and the Lower Part of the Table Lists Selected Measures of Association

Center of bedroom				Surface of bed				Center of family room			
	Gold standard in resonance?				Gold standard in resonance?				Gold standard in resonance?		
Measured in resonance?	Yes	No	Total	Measured in resonance?	Yes	No	Total	Measured in resonance?	Yes	No	Total
Yes	14	5	19	Yes	18	6	24	Yes	18	12	30
No	8	20	28	No	4	13	17	No	4	13	17
Total	22	25	47[b]	Total	19	23	42[c]	Total	22	25	47[b]
Kappa	0.44				0.67				0.33		
95% CI for Kappa	(0.18, 0.70)				(0.46, 0.89)				(0.08, 0.58)		
Sensitivity	0.64				0.82				0.82		
Specificity	0.80				0.68				0.52		
Positive predictive value	0.74				0.75				0.60		
Negative predictive value	0.71				0.76				0.76		

[a]House in resonance if strength of static magnetic field is in one of the two intervals 33.4–44.2 μT and 46.0–55.2 μT.
[b]Gold-standard resonance status could only be determined for 47 of the 51 homes available for analysis.
[c]Gold-standard resonance status could only be determined for 42 of the 51 homes available for analysis.

Static Magnetic Fields and Magnetic Resonance

The upper part of Table 3 presents cross tabulations between resonance status, as assessed using a single visit proxy spot static magnetic field, and resonance status as assessed using the gold standard static magnetic field determined as the average of repeated static magnetic field measurements taken on the surfaces of beds used by subjects. Examination of these tables shows that the majority of entries lie along the diagonals, which happens when the two measures of resonance status agree. For example, a center-of-bedroom single visit proxy static magnetic field was able to correctly assess gold standard on-bed resonance status in 72% of homes. However, some agreement will occur by chance alone. To gauge the agreement beyond that expected by chance, the lower part of Table 3 lists kappa statistics. For the center-of-bedroom field measurement, $\kappa = 0.44$, indicating, at best, only a fair level of agreement between this measure and gold standard resonance status [Fleiss, 1981]. The κ value for the surface of the bed measurement was higher at 0.67.

Table 3 also presents sensitivity, specificity, and positive and negative predictive values characterizing the association between single visit proxy static magnetic fields and gold standard resonance status. Discussion of these measures will be deferred until the next section of this paper.

DISCUSSION AND CONCLUSIONS

The main object of the research reported in this paper was to examine the ability of a single visit proxy static magnetic field to assess resonance status for sleeping subjects. Bowman et al. [1995] based their resonance analysis on static magnetic field data measured at the centers of bedrooms. Presumably, the most relevant exposure occurred while subjects were sleeping, so these authors (implicitly) assumed that resonance status, assessed using a single center-of-bedroom measurement, was sufficient to determine in-bed resonance status. To be able to quantitatively assess the utility of a single visit proxy static magnetic field to assess on-bed resonance status, we included measurements on the surfaces of beds, as well as at the centers of bedrooms and family rooms, in the NCI SV Study measurement protocol.

Among the strengths of our study was the systematic calibration procedures that were followed for the static magnetic-field measurements. Before every use of a meter, the static field at a standardized location (in a technician's home) was measured and checked against previous values for any evidence of meter drift or gross failure. In addition, each meter was returned

periodically (every 264 days on average) to a central laboratory and put through a primary calibration procedure with an accuracy of $\pm 1\%$. All meters passed this test.

The scatter plots in Figures 4 and 5 show that the associations between single visit proxy static magnetic field measurements made at different locations in a home are not strong. The Spearman correlation between static magnetic fields measured at the centers of bedrooms and family rooms in 695 residences located in eight states (Fig. 4) was 0.33 ($P < 10^{-4}$), indicating only a low correlation between these two variables. The comparable value for the NCI SV Study was 0.28 ($P = 0.055$).

The Spearman correlation between single visit proxy static magnetic fields at the centers of family rooms and on the surfaces of beds used by subjects of the NCI SV Study was 0.21. This value is also quite small, although somewhat larger than the comparable value of 0.04 reported by Swanson [1994]; neither correlation was significantly different from zero. Interestingly, when NCI SV Study spot measurements were compared to the on-bed gold standard static magnetic fields, Spearman correlations were somewhat larger (0.41, 0.67, and 0.44 for the center-of-bedroom, surface-of-bed, and center-of-family room spot measurements, respectively).

Of course, the ultimate test of the utility of a single-visit proxy spot static magnetic field measurement for use in resonance analyses like that performed by Bowman et al. [1995] is its ability to correctly predict true on-bed resonance status. The data in Table 3 address this question. Our original expectation, conditioned by Swanson's results [1994], was that, because of local perturbations in static magnetic field levels near beds, a spot measurement made anywhere else would provide, at best, only a very poor measure of true on-bed resonance status. But, spot measurements performed somewhat better than we expected: The kappa statistic for a spot measurement at the center of the bedroom was 0.44, the sensitivity and specificity were 0.64 and 0.80, respectively, and the positive and negative predictive values were 0.74 and 0.71, respectively (Table 3). The latter two values indicate that an assignment of resonance status based on the single-visit proxy spot measurement at the center of a bedroom would correctly gauge resonance status assigned using the gold-standard static magnetic field about 71–74% of the time.

Perhaps not surprisingly, resonance status assessed using a single visit measurement on the surface of the bed was a slightly better surrogate for gold standard resonance status than resonance status based on measurements at the center of the bedroom (Table 3). In fact, since gold standard resonance status was based on the average of a series of static magnetic-field measurements made on the bed during a period of one year, the only reason that a single on-bed measurement was not a perfect surrogate for on-bed resonance status was that the repeated measurements varied sufficiently to affect resonance status in a number of cases. As noted before, we believe the variation in the repeated static field measurements made in each home stemmed from the facts that the position of the meter varied from one measurement to the next (we estimate this variation as being about ± 12 cm) and the increased spatial variability in the field on the surface of the bed attributable to perturbations produced by the ferromagnetic materials used in the bed's construction.

Misclassification of resonance status at the level documented in Table 3 could significantly affect the outcome of a study. To illustrate this point, we have developed the case/control data shown in Table 4 for a hypothetical epidemiologic study based on the following assumptions, which we believe to reasonable estimations of the parameters for actual studies that might be conducted in the future: (i) The probability that a random subject will be in resonance while sleeping is 0.4, a value that is midway between the gold standard values reported in Table 3 and the value extracted from Table 2 in Bowman et al. [1995]. (ii) The study will

TABLE 4. Hypothetical Case/Control Experiment Involving 200 Subjects Exposed to Low and High Levels of 60 Hz Magnetic Fields. Data are Stratified on Resonance Status, Assessed Without Error

	Not-in-resonance subjects			In-resonance subjects		
Exposure	Controls	Cases	OR (CI)[a]	Controls	Cases	OR (CI)[a]
Low	48	41	1.0	32	28	1.0
High	12	10	1.0 (0.4, 2.7)	8	21	3.0 (1.0, 8.8)

[a]Odds ratio (OR) and 95% confidence interval (CI) calculated using Cornfield's method [Kleinbaum et al., 1982].

TABLE 5. Same Data as in Table 4 But Assuming Resonance Status Misclassified

	Not-in-resonance subjects			In-resonance subjects		
Exposure	Controls	Cases	OR (CI)[a]	Controls	Cases	OR (CI)[a]
Low	50	43	1.0	30	26	1.0
High	12	16	1.6 (0.6, 4.0)	8	15	2.2 (0.7, 6.7)

[a]Odds ratio (OR) and 95% confidence interval (CI) calculated using Cornfield's method [Kleinbaum et al., 1982].

consist of 100 cases and an equal number of controls. (iii) Twenty percent of randomly selected subjects will be exposed to "high" levels of 60 Hz magnetic fields. (iv) The risk of disease is very small, but is three times larger when subjects are in resonance *and* simultaneously exposed to high levels of 60 Hz magnetic fields; note that the odds ratios calculated for the not-in-resonance and, separately, in-resonance subjects in Table 4 reflect this assumption about disease risk.

Table 5 lists the same data as in Table 4 except, now, resonance status is assumed to be misclassified with the sensitivity and specificity values of 0.64 and 0.80, respectively, that we obtained for the center-of-bedroom assessment of gold standard on-bed resonance status (Table 3). The odds ratio for the in-resonance subjects has decreased from 3.0 to 2.2 and misclassification of resonance status has led to an artifactual increase in the odds ratio from 1.0 to 1.6 (a 58% increase) for the not-in-resonance group. These changes illustrate our earlier statement that the outcome of an epidemiologic study could be significantly affected by the level of misclassification of on-bed resonance status that would result from the use of a center-of-bedroom measurement of the static magnetic field.

While the data in Table 3 indicate that a static-field measurement on the surface of a bed would provide a slightly better measurement of resonance status than a center-of-bedroom measurement, the overall improvement in sensitivity, specificity, or in predictive values is small. Consequently, our data raise substantial questions about the approach of using spot static-field measurements (even taken on the bed) to estimate resonance status of subjects while they are sleeping. Personal dosimetry may be required to obtain satisfactory results in this regard. Because of these concerns, we have concluded that it is not justified to conduct additional detailed analyses using the NCI/CCG data set [Kleinerman et al., 1997; Linet et al., 1997] to assess the relationship between childhood acute lymphoblastic leukemia and ac magnetic field exposure in subjects classified as being in resonance and, separately, those classified as not being in resonance according to a static magnetic field measured at the centers of their bedrooms.

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