



American Journal of EPIDEMIOLOGY

Volume 134

Number 9

November 1, 1991

Copyright © 1991 by The Johns Hopkins University
School of Hygiene and Public Health

Sponsored by the Society for Epidemiologic Research

ORIGINAL CONTRIBUTIONS

Exposure to Residential Electric and Magnetic Fields and Risk of Childhood Leukemia

Stephanie J. London,¹ Duncan C. Thomas,¹ Joseph D. Bowman,^{1,3} Eugene Sobel,¹ Tsen-Chung Cheng,² and John M. Peters¹

The relation between exposure to electric and magnetic fields in the home, as assessed by measurements, wiring configuration, and self-reported appliance use, and risk of leukemia was investigated in a case-control study among children from birth to age 10 years in Los Angeles County, California. Cases were ascertained through a population-based tumor registry from 1980 to 1987. Controls were drawn from friends and by random digit dialing. Interviews were obtained from 232 cases and 232 controls. Available for analysis were measurements of the magnetic field in the child's bedroom over 24 hours or longer (164 cases and 144 controls), spot measurements of magnetic and electric fields (140 cases and 109 controls), and wiring configuration (219 cases and 207 controls). No clear associations between leukemia risk and measured magnetic or electric fields were seen. An association between the Denver Wertheimer-Leeper wiring configuration and childhood leukemia risk was observed (odds ratio for very high relative to very low current and underground configuration combined = 2.15, 95% confidence interval 1.08–4.28; p for trend = 0.008) and was not substantially altered by adjustment for potential confounding factors. Cases were more likely than controls to report use of several appliances that produce high electric and magnetic fields. Our results support an association between childhood leukemia risk and wiring configuration, but not direct measurements of electric and magnetic fields. *Am J Epidemiol* 1991;134:923–37.

electromagnetic radiation; environmental exposure; leukemia; occupational exposures

Several studies have raised the question of whether elevated exposure to electric and/

or magnetic fields increases childhood leukemia risk. In four studies, exposure was

Received for publication April 23, 1991, and in final form June 11, 1991

Abbreviations: CI, confidence interval; OR, odds ratio.

¹ From the Department of Preventive Medicine, University of Southern California School of Medicine, Los Angeles, CA.

² Department of Electrical Engineering, University of

Southern California School of Engineering, Los Angeles, CA.

³ Current address: National Institute of Occupational Safety and Health, Cincinnati, OH.

Supported by contract no. 799-24 from the Electric Power Research Institute

indirectly assessed by residential wiring configuration (1-4). Higher exposure was related to increased risk in three of those studies (1-3), although given small numbers, not significantly so. Fulton et al. (4) reported no association.

Only two studies provide direct field measurements (2, 5). In a study with few exposed subjects, Tomenijs (5) observed a nonsignificant inverse association between childhood leukemia and magnetic fields measured outdoors, but no association with wiring configuration. With small numbers of leukemias, Savitz et al. (2) observed a nonsignificantly elevated risk for high versus low magnetic fields measured in the home; wiring configuration was more strongly associated with risk. However, in both studies, the measurements were made at a single time point (spot measurements) and may not adequately reflect chronic exposure. Savitz et al. (6) investigated appliance use as an indirect index of electric and magnetic field exposure and observed an association between the use of electric blankets and risk of childhood leukemia.

To address the hypothesis that childhood leukemia is related to increased exposure to electric and magnetic fields, we carried out a case-control study in which we assessed exposure in several ways: measurement of magnetic fields in subjects' homes over 24 hours or more, spot measurements of both electric and magnetic fields, and indirect assessment of exposure by wiring configuration and self-report of appliance use. We had previously published a report of childhood leukemia in relation to parental occupational exposures and other environmental chemical exposures; electric and magnetic fields were not measured (7). In this study,

we returned to make measurements on cases from the original study diagnosed from 1980 to 1984 and their controls and added new cases and controls ascertained between 1985 and 1987.

MATERIALS AND METHODS

Subjects

All newly diagnosed cases of leukemia occurring between 1980 and 1987 in children from birth to age 10 years and resident in Los Angeles County, California, were eligible. Cases were identified by the Los Angeles County Cancer Surveillance Program (8, 9). We asked permission of each patient's physician to contact the parents for interview. With the physician's consent, we attempted to locate and contact the patient's parents to gain permission for interview and for electric and for magnetic field measurements.

We interviewed 232 case-control pairs (table 1). The original report by Lowengart et al. (7) included data on 123 cases diagnosed from 1980 to 1984 and their matched controls. An additional 27 case-control pairs identified were excluded from the original report because of missing information. The first 65 controls were drawn from friends of cases; all subsequent controls were selected by random digit dialing. For the supplementary study, we attempted to recontact all 150 pairs identified from the original study and completed interviews for 139 cases and 131 controls. Additionally, we replaced eight controls (including three friend controls) whom we could not reach with new controls contacted through random digit dialing. We also interviewed 93 cases diagnosed from 1985 to 1987 and 93 controls selected by random digit dialing.

In the random digit dialing procedure, the first five digits of the case's telephone number were used, followed by a random choice of the last two digits. We attempted to individually match on sex, ethnicity (black, white, Hispanic, and Asian), and age. The age-matching algorithm varied with the case's age: within 1 year of the case's age at the time of diagnosis for cases under age 2

Reprint requests to Dr. Stephanie London, University of Southern California Medical School PMB B306, 1420 San Pablo Street, Los Angeles CA 90033.

The authors acknowledge the expert assistance of Leopoldo Herrera, Joan Howland, Donald Krim, William Lapworth, Isabel Nader, Monica Rosales, Zide Qian, Thomas Trauger, and Dr. Li-Jean Wang. We are grateful for help provided by Southern California Edison, the Los Angeles Department of Water and Power, Pasadena Municipal Services, Burbank Water and Light, and Glendale Water and Electric.

TABLE 1. Number of cases and controls entered into the study and type of exposure measurement available, Los Angeles County, California, 1980-1987

| | Cases | Controls | Matched pairs |
|---|-------|----------------|---------------|
| Interview data | | | |
| Eligible for interview | 331 | 257 | |
| Physician refusal | 22 | | |
| Parent refusal | 24 | 25 | |
| Not traceable | 33 | Not applicable | |
| Mother interviewed | 232* | 232 | 232 |
| Father interviewed | 232 | 230 | |
| Direct | 188 | 164 | |
| From mother | 44 | 66 | |
| 24-hour magnetic field measurements | | | |
| Subjects with residences eligible for measurements† | 205 | 187 | |
| Subjects requiring measurement of 2 houses | 10 | 10 | |
| Residences eligible for measurements | 215 | 197 | |
| Refusals | 26 | 21 | |
| Lost or invalid data | 20 | 27 | |
| Residences with valid measurements | 169 | 149 | |
| Subjects with 24-hour magnetic field measurements on at least one residence | 164 | 144 | 108 |
| Spot measurements | | | |
| Subjects with spot measurement in child's bedroom on at least one residence | 140 | 109 | 71 |
| Writing map | | | |
| Subjects with wiring map on at least one residence | 219 | 207 | 194 |

* Interview obtained with an additional 20 subjects for whom no control could be obtained

† From among 232 case-control pairs for whom mother was interviewed.

years, within 2 years for cases aged 3-5 years, and within 3 years for cases aged 6 years or older. When the matching rules were not met after 300 calls, we relaxed matching criteria first on ethnicity, then on sex, and finally on age. Cases and controls were comparable with regard to matching factors (table 2).

Nine attempts, at different times of the day and week, were made to contact a resident at each telephone number selected by the random digit dialing procedure. Upon contact, if a match occurred, we requested permission to enroll the parents of the control in the study. For the original study (7), our records do not allow computation of the number of contacts per eligible control identified. In the supplementary study, 4,424

telephone numbers were called, and 800 yielded no answer after nine attempts. Among 3,624 contacts made, 3,303 subjects were ineligible, eligibility could not be determined for 208, 113 were eligible, and 102 agreed to participate, of whom one was not used.

Questionnaires

We attempted to interview both parents. When the father could not be interviewed, we asked the mother to provide information (table 1). Interviews were conducted in either English or Spanish. The interview included a complete history of the child's residences, demographics, basic medical history of the child and parents, use of medi-

TABLE 2. Demographic information for 232 cases and 232 controls with interview data, Los Angeles County, California, 1980-1987

| Item | Cases | | Controls | | Cases (mean \pm SD*) | Controls (mean \pm SD) |
|--|-------|------|----------|------|---------------------------|-----------------------------|
| | No. | % | No. | % | | |
| Sex | | | | | | |
| Male | 130 | 56.0 | 129 | 55.6 | | |
| Female | 102 | 44.0 | 103 | 44.4 | | |
| Ethnicity (%) | | | | | | |
| Non-Hispanic white | 117 | 50.4 | 126 | 54.3 | | |
| Hispanic | 85 | 36.6 | 87 | 37.6 | | |
| Black | 13 | 5.6 | 13 | 5.6 | | |
| Asian | 17 | 7.3 | 6 | 2.6 | | |
| Child's age (years) at reference date | | | | | 3.4 \pm 2.3 | 3.3 \pm 2.6 |
| Mother's age (years) at child's birth | | | | | 30.7 \pm 6.10 | 30.4 \pm 6.12 |
| Father's age (years) at child's birth | | | | | 29.6 \pm 6.42 | 30.1 \pm 7.24 |

* SD, standard deviation.

cations, and occupational history for both parents. We also gathered information on the location and temporal pattern of the child's activity, history of appliance use, and exposure to environmental chemicals, recreational drugs, and incense.

Determining residences for measurements

We sought electric and magnetic field measurements for at least one residence per subject. To take into account potential variability in latency with age of diagnosis, we defined the "etiologic" period as the interval between the mother's last known menstrual period preceding the birth of the case up to a reference date keyed to the date of diagnosis of leukemia. The reference date was the date of diagnosis for children aged 1 year or less, the date of diagnosis minus 6 months for children aged 1 to 2 years, and the date of diagnosis minus 1 year for children greater than age 2.

If the case or control had lived in the current residence during most of the etiologic period, we surveyed the electric and magnetic fields in that residence. If a past residence was inhabited for the longest part of the etiologic period and was located in Southern California, we measured that residence. If two or more residences in Southern

California were inhabited for approximately equal parts of the etiologic period, we surveyed the most recent residence for which permission was obtained. If a past residence was inhabited for the longest part of the etiologic period and was located outside Southern California, we surveyed the residence in Southern California inhabited for the longest time, provided that the duration of residence exceeded 25 percent of the etiologic period. If the time lived in the first house was greater than 25 percent but less than 40 percent and the time in the second house was greater than 25 percent of the etiologic period, we attempted to measure the second house as well.

When the house identified was no longer occupied by the case or control, we sought permission from the current resident to make measurements. In some instances, the occupant allowed us only to place the instrument for 24-hour measurement of magnetic fields or to take a few spot measurements. When we could not gain access to the residence, we made outdoor measurements.

Twenty-seven cases (12 percent) and 45 controls (20 percent) did not have a home eligible for measurements. Twenty-four-hour magnetic field measurements were available for 80 percent of the cases and 77 percent of the controls, and spot measurements were available for 68 percent of cases

and 58 percent of controls with residences eligible for measurement (table 1). The average proportion of the etiologic period covered by available measurements was 78 percent for cases and 80 percent for controls. Only 43 percent of cases (100 of 232) and 34 percent of controls (80 of 232) had lived for the entire etiologic period in the house(s) we measured. However, for 63 percent of the cases and 55 percent of the controls, our measurements covered at least half the etiologic period. There were no substantial differences between cases and controls in any of the available measures of coverage of the etiologic period (data not shown).

We drew wiring maps for all subject residences in Southern California for which we obtained complete addresses. Wiring maps were available on at least one residence for 94 percent of cases and 89 percent of controls (table 1).

Electric and magnetic field measurements

For each willing subject, we conducted a residential survey to measure domestic electric and magnetic fields from the electrical distribution system and appliances and to record other variables needed to estimate the child's exposure. Measurements were made from 1987 to 1989 by field technicians blinded to case-control status.

The protocol for measuring the electric and magnetic fields attempted to account for the effects of variation by time of day, location, frequency, and power usage. Time was accounted for by measuring over at least 24 hours the magnetic field at the place where the child's bed had been during the etiologic period. Location was accounted for by taking spot measurements in three to four locations within the house and up to three locations outside. The four interior locations were the main living area, parent's bedroom, child's sleeping area (when distinct), and the living area closest to the electrical distribution wiring unless that room was one of the other three. Outdoor measurements were made in the front yard and/or backyard areas which the child used (as determined in

the telephone interview) and over the water pipe. The frequency spectrum was accounted for by taking spot measurements in both the flat and linear modes of frequency response. For comparability with the study of Savitz et al. (2) and to account for fields generated by outside power lines versus in-home sources, we performed measurements with indoor appliances off (low power) and with appliances on (normal power).

To measure the magnetic flux density and the electric field, we used a model 113 Power Frequency Field Meter (Denometer) (Electric Field Measurements West, Stockbridge, Massachusetts). The Denometer was mounted on a tripod made of nonconducting polycarbonate plastic and placed as close as possible to the center of each room and outdoor play area. To measure the field intensity, we placed the electric field antenna (the meter casing) and the magnetic field antenna (an induction coil) in three orthogonal directions. In the child's bedroom, we measured the static magnetic field with a flux-gate magnetometer (model MAG-01, Bartington Instruments Ltd., Oxford, United Kingdom) and also measured the harmonic content of the magnetic field.

To measure the magnetic field over a 24-hour period or longer, we first used the IREQ instrument (Institut de Recherche d'Hydro Quebec, Varennes, Quebec, Canada) and later the EMDEX instrument (ENERTECH Consultants, Campbell, California, and Electric Field Measurements, West Stockbridge, Massachusetts). The IREQ recorded the magnetic field in three dimensions every 50 seconds, the EMDEX every 10 seconds.

Field personnel recorded the location of the child's bedroom and bed, building type, construction material, outdoor temperature, and electricity usage from the watt-hour meter. They explained the purpose of the study to the residents and obtained informed consent.

The electric and magnetic fields were expressed as the resultant of readings in three orthogonal directions in units of milligauss (mG) for magnetic fields and volts per meter for electric fields. However, for the water

pipe magnetic field, we used the horizontal component of the field perpendicular to the pipe.

During data collection, the accuracy of the electric and magnetic field measurements was assessed by repeated calibrations of the magnetic field instruments, replicate measurements in residences, regular reliability checks, and postmeasurement checks for data integrity.

Magnetic field instruments were calibrated in a single circular coil to have a unit response at 60 Hz, the frequency of the alternating current electric power supply in the United States. Since the instruments have an approximately flat response to other frequencies in the 30- to 300-Hz (extremely low frequency) range, the measured field magnitudes are dominated by the 60-Hz component, which accounts for over 76 percent of residential magnetic fields (10). The mean bias, used to compare the calibration coil with the instrument, was 5.3 percent or less for the EMDEX and IREQ instruments and the Denometers. This number includes fluctuations in the ambient magnetic field and therefore overestimates the true inaccuracy (10). For the electric field mode on the Denometer, we used the factory calibration.

The reproducibility of the magnetic field measurements under field conditions was determined from replicate measurements in residences. The Denometer (spot) measurements were repeated over 5–10 minutes in 55 residences. Reproducibility of EMDEX readings was determined by installing two meters in the same carrying case at each of seven residences. The ratio of the between- to within-residence coefficients of variation was 2.6 for the spot measurements and 4.1 for the EMDEX measurements. Because we switched from using IREQ to EMDEX instruments during the study, we also compared simultaneous EMDEX-IREQ measurements in another seven subject residences. The within-residence coefficient of variation was 19.9 percent compared with the within-residence coefficient of variation for replicate EMDEX measurements of 17.7 percent, suggesting that the mixing of IREQ

and EMDEX measurements is not an important additional source of measurement error. In addition, there was no systematic difference between the IREQ and EMDEX measurements.

Reliability readings on Denometers and IREQ and EMDEX instruments were done regularly, and repairs were made when necessary. We inspected the recorded data after every measurement and repeated measurements where possible when we detected malfunctions. The IREQ instruments were prone to malfunctions and were therefore replaced by the EMDEX instruments during the study.

Wiring configuration

Wiring configuration was used to predict the exposure to electric and magnetic fields in the residences that were not accessible for field measurements and to obtain an estimate of long-term exposures that might be more stable than the short-term measurements. We blindly classified wiring configurations at residences according to the system of Wertheimer and Leeper (11) in order to use the same exposure measure which was associated with childhood cancer risk in previous studies (1, 2). The Denver Wertheimer-Leeper classification was developed to predict magnetic fields under electrical lines in the Denver, Colorado, area and has been validated against measurements inside residences in the Denver area (12) and the state of Washington (10). We also predicted the magnetic field on the basis of detailed features of the wiring configuration by using the equation of Kaune et al. (10).

To enable classification of wiring configuration, the field technician drew sketches of the house and all overhead electrical transmission and distribution facilities within 150 feet. From utility maps, data on distances, line voltage, transformer capacities, wire sizes, and underground lines were collected. A scale map of the wiring was drawn on a personal computer using the FMS/AC software package (Facility Mapping Systems Inc., Mill Valley, California), and additional data on the electrical features

were entered. We extracted wiring configuration variables into a data base and used a computer algorithm to blindly assign Wertheimer-Leeper classifications. The categories were underground, very low, ordinary low, ordinary high, very high, and mixed.

We also classified houses according to the location of wires (overhead or underground) and wiring of the primary distribution lines. The primary distribution lines in the Los Angeles area use a neutral wire (Wye transformer), no neutral wire (Delta), or combinations of both. Conversely, a house might not be within 150 feet of a primary distribution line (either Wye or Delta primary). Distribution wiring in Los Angeles differs from Denver, Washington, and most of the rest of the United States because of the frequent use of Delta primary distribution lines.

Statistical analysis

Table 1 contains details on the data available for analysis. The 232 matched pairs with residential histories serve as the basic study population. The numbers available for analysis of particular exposure variables are reduced because we did not have all measurements on all subjects.

Comparisons between the various exposure measurements were made using Spearman rank correlations (13). Comparisons of measurements and wiring configuration categories were done using geometric means because the measurements were well-described by lognormal distributions.

The primary test of hypotheses about the relation between leukemia risk and electric and magnetic field exposure was based on logistic regression methods (14). Although mean exposures as assessed by 24-hour or longer magnetic field measurements (henceforth referred to as 24-hour magnetic field measurements) were similar in the matched and unmatched sets of cases, the mean exposure was lower among the matched than among the unmatched set of controls, suggesting that the matched subjects might not be representative of the entire study group. Therefore, we carried out unmatched as well

as matched analysis. The two gave virtually identical results, and therefore for conciseness, we present only the unmatched results for analyses of measurements and wiring configuration. For analyses of appliance data which used only questionnaire data, available on all subjects, we present matched results. Inclusion of terms for the matching factors in the unmatched logistic regressions made only a trivial change in the parameter estimates or their standard errors.

Each exposure variable was categorized into four levels, based on the 50th, 75th, and 90th percentiles of its distribution among cases and controls combined. Tests for trend are presented, with the exposure variable treated as a continuous variable and as an ordered categorical variable. Three highly influential 24-hour magnetic field measurements (two cases and one control) were excluded from all analyses involving continuous scale data, but were included in analyses involving ordered categories.

For our primary hypothesis, we concentrated on the arithmetic mean of the 24-hour magnetic field measurements, the child's bedroom spot measurement at low power, and the Denver Wertheimer-Leeper wiring configuration. However, in order to avoid missing an association if these parameters were not the best choices, we also examined other summaries of the 24-hour magnetic field measurements and other spot measurements, as well as the Kaune wiring configuration (10) and Wye/Delta wiring variables. Analyses of the relations among the different types of measurements were performed by using residences as the observational unit, while analyses of the relation of measurements to leukemia risk were done by using subjects as the observational unit. When measurements for a subject were taken in two residences, we calculated the average of the two measurements weighted by the time spent in each residence. When wiring maps were available for more than one residence, we used the Denver Wertheimer-Leeper wiring configuration for the house lived in the longest.

Various potential occupational and environmental confounders were first examined

TABLE 3. Results of measurements by case-control status, Los Angeles County, California, 1980-1987

| Exposure variable | Cases | | Controls | |
|--|-------|--------------------|----------|--------------------|
| | No. | Mean \pm SD* | No. | Mean \pm SD |
| 24-hour magnetic field measurements (mG) | 162† | | 143 | |
| Arithmetic mean | | 1.14 \pm 1.34 | | 1.15 \pm 1.57 |
| Median | | 1.02 \pm 1.15 | | 1.02 \pm 1.42 |
| Geometric mean | | 0.99 \pm 1.11 | | 1.01 \pm 1.41 |
| 90th percentile | | 1.79 \pm 2.69 | | 1.86 \pm 3.04 |
| % time over 2.5 mG | | 10.15 \pm 24.16 | | 7.73 \pm 21.71 |
| Spot measurements: magnetic field (mG) | | | | |
| Indoor | 140 | | 109 | |
| Child's bedroom | | | | |
| Normal power | | 1.11 \pm 2.80 | | 0.60 \pm 0.79 |
| Low power | | 0.60 \pm 0.79 | | 0.55 \pm 0.76 |
| Linear mode | | 0.76 \pm 1.13 | | 0.61 \pm 0.77 |
| Static field | | 443.72 \pm 31.78 | | 447.80 \pm 48.14 |
| Mean indoor (excluding bedrooms) | | | | |
| Normal power | | 0.69 \pm 0.97 | | 0.66 \pm 0.92 |
| Low power | | 0.63 \pm 1.30 | | 0.60 \pm 0.88 |
| Outdoor | | | | |
| Mean outdoor (excluding water pipes) | 144 | 0.57 \pm 0.64 | 116 | 0.68 \pm 1.01 |
| Over water pipe | 168 | 0.62 \pm 1.21 | 153 | 0.64 \pm 1.47 |
| Spot measurements: electric field (V/m) | | | | |
| Child's bedroom normal | 136 | 7.48 \pm 9.84 | 108 | 7.98 \pm 12.27 |
| Mean outdoor | 144 | 1.87 \pm 2.33 | 116 | 2.63 \pm 4.21 |

* SD, standard deviation.

† Two cases and one control with influential values are deleted from this table and from other analysis of continuous variables.

univariately, treating each as dichotomous with standard matched pair methods. We then included those that showed an association with leukemia risk in multiple logistic regression analyses with each of the three primary exposure variables. We retained potential confounders that made at least a suggestive contribution (one-tailed *p* value for the coefficient less than 0.10) to any of these three regressions in the final models.

RESULTS

Table 3 contains a summary of the distributions of the available exposure measurements by case-control status. The number of 24-hour magnetic field measurements exceeds the number of spot measurements because in several residences we were allowed to place the instrument for measuring magnetic fields over 24 hours but not to take spot readings. The number of outdoor spot measurements over the water pipe exceeds

all other spot measurements because we could take these measurements without permission. For some measurements, the variability was unequal between cases and controls. However, in general the distributions were similar.

We explored the relation between the Denver Wertheimer-Leeper configuration classification and measured exposures (table 4). The very low category generally had the lowest values, and the very high category clearly had the highest values for the magnetic fields from both the 24-hour and spot measurements, with the exception of the measurement for static fields. The underground category was lower than the very low category for a few measurements but was otherwise similar to very low. The trend across categories was evident for all summary parameters of the 24-hour magnetic field measurements. Those wiring configurations with both underground and overhead components were categorized as

TABLE 4. Geometric means of exposure measurements by Denver Wertheimer-Leeper wiring configuration classification: Los Angeles County, California, 1980-1987

| Variable | Category of Denver Wertheimer-Leeper wiring configuration | | | | | |
|---|---|----------|--------------|---------------|-----------|--------|
| | Underground | Very low | Ordinary low | Ordinary high | Very high | Mixed |
| No. of residences | 39 | 58 | 248 | 214 | 112 | 21 |
| 24-hour magnetic field measurements (mG) (no.)* | 19 | 48 | 69 | 112 | 53 | 5 |
| Arithmetic mean | 0.48 | 0.47 | 0.65 | 0.72 | 1.15 | 0.41 |
| Median | 0.45 | 0.42 | 0.58 | 0.66 | 1.07 | 0.41 |
| Geometric mean | 0.45 | 0.40 | 0.58 | 0.66 | 1.03 | 0.41 |
| 90th percentile | 0.64 | 0.64 | 0.92 | 1.04 | 1.58 | 0.55 |
| % time over 2.5 mG | 0.33 | 3.68 | 11.64 | 6.39 | 16.63 | 6.91 |
| Spot measurements: magnetic field (mG) | | | | | | |
| Child's bedroom (no.) | 14 | 26 | 77 | 86 | 37 | 2 |
| Normal power | 0.22 | 0.19 | 0.31 | 0.33 | 0.61 | 0.11 |
| Low power | 0.17 | 0.17 | 0.22 | 0.29 | 0.60 | 0.11 |
| Linear in frequency | 0.20 | 0.18 | 0.24 | 0.32 | 0.73 | 0.43 |
| Static field | 453.28 | 436.47 | 449.25 | 443.20 | 436.53 | 438.62 |
| Mean indoor (excludes bedroom) | | | | | | |
| Normal power | 0.24 | 0.21 | 0.33 | 0.32 | 0.69 | 0.48 |
| Low power | 0.16 | 0.19 | 0.25 | 0.29 | 0.60 | 0.28 |
| Outdoor | | | | | | |
| Mean outdoor (excludes water pipes) | 0.17 | 0.20 | 0.29 | 0.32 | 0.69 | 0.27 |
| Over water pipe | 0.14 | 0.26 | 0.24 | 0.28 | 0.37 | 0.24 |
| Spot measurements: electric field (V/m) | | | | | | |
| Child's bedroom normal | 3.74 | 3.00 | 3.83 | 4.83 | 3.57 | 5.01 |
| Mean outdoor | 0.29 | 0.63 | 1.04 | 1.26 | 1.49 | 0.57 |

* Three residences with influential values excluded.

mixed. Because the mixed category was too small to allow stable estimates and was not in the original Denver Wertheimer-Leeper scheme, we excluded this category from the wiring configuration hierarchy.

Mean 24-hour magnetic field measurements highly correlated with spot measurements in the child's bedroom at both low power (Spearman correlation = 0.63) and normal power (Spearman correlation = 0.67). Electric fields were not well-correlated with 24-hour magnetic field measurements (Spearman correlation = 0.03) or spot magnetic field measurements (Spearman correlation = 0.16, low power).

We evaluated the representativeness of houses with incomplete exposure measurements. Low-power spot measurements were similar in houses without (mean = 0.31 mG, geometric standard deviation = 4.83 mG) and those with (mean = 0.27 mG, geometric standard deviation = 3.86 mG) 24-hour magnetic field measurements. The percent-

age of subjects in the very high category of the Denver Wertheimer-Leeper configuration was similar among subjects with 24-hour magnetic field measurements (17 percent) and those without (15 percent). These comparisons suggest that among study subjects, magnetic field exposure was not related to the willingness of subjects to allow indoor measurements.

We evaluated leukemia risk in relation to several measures of exposure. The risk associated with 24-hour magnetic field measurements in the child's bedroom is presented in table 5. Although the odds ratio was greatest in the highest category of exposure, there was no consistent trend. Several summary statistics of the 24-hour magnetic field measurements were examined—arithmetic mean, geometric mean, median, 90th percentile, and percent of time over 2.5 mG—and none was associated with risk.

We examined spot measurements of low-

power magnetic fields in relation to childhood leukemia risk (table 6). We found no association regardless of the choice of cut-points for the highest category. Spot measurements of the magnetic field in the child's bedroom at normal power, of the linear mode, and of the static magnetic field were not associated with risk, nor were the mean of spot measurements in other rooms or outdoors (data not shown).

We evaluated electric fields in the child's bedroom and found no association with leukemia risk. Relative to the bottom half of the distribution, the odds ratios for the 50–74th percentiles were 0.66 (95 percent confidence interval (CI) 0.36–1.21), for the 75–89th percentiles, 1.11 (95 percent CI 0.58–2.56), and for the 90th percentile and above 0.44 (95 percent CI 0.19–1.01) with a *p* value for trend of 0.22. Likewise, electric field spot measurements taken elsewhere inside the house or outdoors were not associated with leukemia risk.

In evaluating the association between Denver Wertheimer-Leeper wiring configura-

tion classification and leukemia risk, we chose to combine the very low and under-ground categories into a single reference group to provide more stable estimates. As shown in table 7, there was a significant association between Denver Wertheimer-Leeper wiring configuration classification and leukemia risk.

We explored possible effect modification by age, sex, and race of the association between leukemia risk and our three primary exposure variables and found none. Although there were only 33 acute nonlymphocytic leukemias among cases with wiring configuration available, associations with this tumor type did not differ substantially from those with acute lymphocytic leukemia (data not shown).

The associations between childhood leukemia risk and 24-hour magnetic field measurements, spot measurements, and Denver Wertheimer-Leeper wiring configuration classification did not vary materially by the proportion of the etiologic period covered by measurements. The association between

TABLE 5. Leukemia risk in relation to the arithmetic mean of 24-hour magnetic field measurements in the child's bedroom, Los Angeles County, California, 1980–1987*

| Exposure category (percentile) | Exposure range (mG) | Cases | Controls | OR† | 95% CI† | <i>p</i> for trend |
|--------------------------------|---------------------|-------|----------|------|-----------|--------------------|
| 0–49 | 0.00–0.67 | 85 | 69 | 1.00 | | |
| 50–74 | 0.68–1.18 | 35 | 42 | 0.68 | 0.39–1.17 | |
| 75–89 | 1.19–2.67 | 24 | 22 | 0.89 | 0.46–1.71 | |
| 90–100 | ≥2.68 | 20 | 11 | 1.48 | 0.66–3.29 | |
| | | | | | | 0.94 (continuous) |
| | | | | | | 0.74 (ordinal) |

* Two cases and one control are included in the analysis of categorical, but not continuous data

† OR, odds ratio, CI, confidence interval.

TABLE 6. Leukemia risk in relation to low-power magnetic field spot measurements in child's bedroom, Los Angeles County, California, 1980–1987

| Exposure category (percentile) | Exposure range (mG) | Cases | Controls | OR* | 95% CI* | <i>p</i> for trend |
|--------------------------------|---------------------|-------|----------|------|-----------|--------------------|
| 0–49 | 0–0.31 | 67 | 56 | 1.00 | | |
| 50–74 | 0.32–0.67 | 34 | 28 | 1.01 | 0.61–1.69 | |
| 75–89 | 0.68–1.24 | 23 | 14 | 1.37 | 0.65–2.91 | |
| 90–100 | ≥1.25 | 16 | 11 | 1.22 | 0.52–2.82 | |
| | | | | | | 0.50 (continuous) |
| | | | | | | 0.61 (ordinal) |

* OR, odds ratio, CI, confidence interval.

leukemia and wiring configuration was slightly stronger when the analysis was limited to the residence lived in longest compared with an analysis of subjects with multiple residences weighted by the proportion of the etiologic period spent in the each residence (data not shown).

To evaluate potential confounders, we examined the univariate associations between self-reported exposures to factors that had

been found to be associated with childhood cancer in previous studies in addition to self-reported sources of electric and magnetic field exposure such as appliance use and occupational exposure.

Table 8 contains data on children's and mothers' exposures to electrical appliances. Questions about children's exposures were based on the regular use (at least once a week), and questions about mothers in-

TABLE 7. Leukemia risk in relation to Denver Wertheimer-Leeper wiring configuration classification, Los Angeles County, California, 1980-1987

| Exposure category* | Cases | Controls | OR† | 95% CI† | p for trend |
|--------------------|-------|----------|-------|-----------|--------------------------|
| Underground | 11 | 11 | 1.00‡ | | |
| Very low | 20 | 27 | | | |
| Ordinary low | 58 | 75 | 0.95 | 0.53-1.69 | |
| Ordinary high | 80 | 68 | 1.44 | 0.81-2.56 | |
| Very high | 42 | 24 | 2.15 | 1.08-4.26 | |
| | | | | | 0.008 (4 categories) |
| | | | | | 0.012 (all 5 categories) |

* Mixed overhead/underground removed (eight cases and two controls).

† OR, odds ratio, CI, confidence interval

‡ Reference category is underground and very low combined. Wiring configuration classification for the residence lived in the longest was used

TABLE 8. Leukemia risk in relation to self-reported appliance use by children and mothers, Los Angeles County, California, 1980-1987

| Appliance | Discordant pairs (cases/controls) | Matched OR* | 95% CI* |
|--|-----------------------------------|-------------|-------------|
| Child's exposure (at least once a week) | | | |
| Bedroom air conditioner | 7/13 | 0.54 | 0.21-1.25 |
| Black-and-white television | 64/43 | 1.49 | 1.01-2.23 |
| Electric clock | 61/46 | 1.33 | 0.90-1.97 |
| Dial | 26/14 | 1.86 | 0.97-3.83 |
| Digital | 43/39 | 1.10 | 0.71-1.72 |
| Color television | 34/32 | 1.06 | 0.66-1.74 |
| Curling iron | 6/1 | 6.00 | 0.72-104.80 |
| Electric blanket | 7/1 | 7.00 | 0.86-121.80 |
| Electric fan | 54/45 | 1.20 | 0.81-1.80 |
| Electric clippers | 1/1 | 1.00 | 0.06-19.60 |
| Electric hair dryer | 31/11 | 2.82 | 1.42-6.32 |
| Electric space heater | 29/20 | 1.45 | 0.82-2.66 |
| Microwave oven | 25/31 | 0.81 | 0.48-1.36 |
| Water bed | 12/12 | 1.00 | 0.45-2.29 |
| Video game | 22/14 | 1.57 | 0.80-3.27 |
| Mother's exposure (any during pregnancy) | | | |
| Water bed | 14/21 | 0.67 | 0.34-1.28 |
| Bedroom air conditioner | 21/23 | 0.91 | 0.51-1.66 |
| Electric blanket | 23/19 | 1.21 | 0.66-2.29 |
| Electric fan | 51/44 | 1.16 | 0.77-1.75 |
| Electric space heater | 20/17 | 1.18 | 0.62-2.32 |

* OR, odds ratio; CI, confidence interval.

volved any exposure during pregnancy. For the 15 items we asked about for children, 11 odds ratios were greater than unity; two were statistically significant (black-and-white television and electric hair dryer use). The highest odds ratios were for the use of electric blankets and curling irons, but these estimates were unstable because of small numbers. In contrast, mothers of cases did not report higher exposures to appliances during their pregnancy than did mothers of controls.

We examined associations between leukemia risk and environmental variables such as self-reported use (ever or never) of insecticides (indoors and outdoors), incense, drugs, and cigarettes during the etiologic period. We also examined the type of dwelling (apartment versus house), construction materials (stucco, wood, or other), and heating (gas versus other, electric versus other). Statistically significant elevations in the univariate odds ratio were found only for incense use (odds ratio (OR) = 2.78, 95 percent CI 1.30–6.88) and insecticide use inside the house (OR = 2.48, 95 percent CI 1.49–4.36). Of note, the type of dwelling was not related to risk (OR = 1.30, 95 percent CI 0.86–1.99).

We examined the associations between leukemia risk and self-reported parental oc-

cupational exposures. Eight broad categories of paternal and maternal occupational exposures during three time periods (prepregnancy, pregnancy, and postpregnancy) were used. The categories were: solvents, plastics, paints (spray and all paints), petroleum products, metals, insulation materials, non-ionizing radiation, and "other" chemicals. Univariate odds ratios were elevated in all but two categories for paternal exposure (metals and insulation materials), but estimates were unstable (data not shown). The strongest associations were for mothers' exposure to nonionizing radiation (OR = 4.08, 95 percent CI 1.1–39.88), and father's exposure to spray paint during the pregnancy (OR = 2.08, 95 percent CI 1.07–4.39) and to other chemicals postpregnancy (OR = 2.00, 95 percent CI 1.08–4.00).

We also examined possible confounding by socioeconomic status as assessed by social class in five categories derived from census tract and father's occupation, classified as blue- or white-collar. These indices of social class did not confound the association between Wertheimer-Leeper wiring configuration classification and leukemia risk.

The following variables met our criteria for inclusion in multiple logistic regression analysis models presented in table 9: use of incense; use of indoor pesticide; children's

TABLE 9. Risk of leukemia in relation to 24-hour magnetic field measurements and Denver Wertheimer-Leeper wiring configuration class, with and without adjustment for confounding variables, Los Angeles, California, 1980–1987

| Exposure variable and model | Percentile | | | | | | | p for trend |
|--|--------------------------|--------------|-----------|---------------|-----------|-----------|-----------|-------------|
| | 0–49 | 50–74 | | 75–89 | | 90–100 | | |
| | | OR* | 95% CI* | OR | 95% CI | OR | 95% CI | |
| 24-hour magnetic field measurements | | | | | | | | |
| Crude | 1.00 | 0.68 | 0.39–1.17 | 0.89 | 0.46–1.71 | 1.48 | 0.66–3.29 | 0.94 |
| Adjusted† | 1.00 | 0.66 | 0.36–1.19 | 0.94 | 0.47–1.89 | 1.69 | 0.71–4.00 | 0.52 |
| Wiring code | | | | | | | | |
| | Underground and very low | Ordinary low | | Ordinary high | | Very high | | |
| Crude | 1.00 | 0.95 | 0.53–1.70 | 1.44 | 0.81–2.56 | 2.15 | 1.08–4.28 | 0.008 |
| Adjusted† | 1.00 | 0.78 | 0.40–1.49 | 1.46 | 0.78–2.74 | 1.73 | 0.82–3.66 | 0.017 |

* OR, odds ratio; CI, confidence interval.

† Adjusted for self-reported use of indoor pesticides, hair dryers, black-and-white televisions, and fathers' occupational exposure to spray paint during pregnancy and to other chemical exposures postpregnancy.

exposure to hair dryers and black-and-white televisions; and occupational exposure of the father to spray paint during pregnancy and to other chemicals postpregnancy. Although some variables slightly increased and some slightly decreased the slope estimate for Denver Wertheimer-Leeper wiring configuration classification, none changed it by more than 10 percent, and the net effect of adjustment for all variables was to reduce the slope by 3 percent while increasing its standard error by 8 percent, thus weakening its statistical significance from 0.008 to 0.017. Adjustment for these confounders had only a minimal effect on the dose-response or point estimates for the mean of 24-hour magnetic field measurements (table 9).

DISCUSSION

We found little support for the hypothesis that increased exposure to magnetic fields, as assessed by 24-hour measurements or spot measurements, increases the risk of childhood leukemia. Electric fields were also not materially associated with leukemia risk. However, consistent with earlier studies in Denver (1, 2), we observed a positive association between the Denver Wertheimer-Leeper wiring configuration classification and leukemia risk. This association was only slightly diminished by adjustment for self-reported factors associated with leukemia risk in these data.

Although we observed significant elevations in risk for children's exposure to electric hair dryers and black-and-white televisions, higher use was reported by case parents than control parents for most appliances. In a smaller study, Savitz et al. (6) reported no association with the use of hair dryers. Consistent with Savitz et al. (6), we observed a nonsignificant elevation in risk for the use of electric blankets, although the point estimate is more unstable in our data. The possibility that recall bias and selection bias influenced the association between disease and self-reported appliance use in both studies makes these findings difficult to interpret. Nonetheless, hair

dryers produce substantial magnetic and electric fields, and cases were more likely than controls to report use of dial clocks, which generate much higher fields than digital ones.

This is the first study of childhood leukemia with extended measurements of magnetic fields. There are few data on measured magnetic fields in relation to childhood leukemia risk. Savitz et al. (2) observed no important association between childhood leukemia and indoor spot measurements. Tomenius (5) found a nonsignificant inverse association between outdoor spot measurements and childhood leukemia risk.

Previous studies have generally found an association between wiring configuration as a surrogate for elevated electric and magnetic field exposures and childhood leukemia risk. Wertheimer and Leeper (1) observed a two- to threefold elevation in leukemia risk for Denver children living in homes with high-current relative to low-current configurations. Although Fulton et al. (4) originally reported no association between wiring configuration and leukemia risk in a study in Rhode Island, when the analysis was restricted to addresses of children under age 8 years, an approximate 70 percent increase in risk was observed for living in a house with a high-current configuration (15). Savitz et al. (2) observed an odds ratio of 1.54 (95 percent CI 0.90-2.63) for dichotomous high- versus low-current wiring configuration among 97 leukemia cases. They observed a correlation between measured magnetic fields and five levels of Denver Wertheimer-Leeper wiring configuration, a finding confirmed in our study by using 24-hour magnetic field measurements.

The finding of a stronger association between leukemia risk and an indirect measure of magnetic fields (wiring configuration) than direct measures (24-hour magnetic field measurements as well as spot measurements of electric and magnetic fields) suggests two fundamentally different interpretations.

One possibility is that a true etiologic relation exists between residential exposure to higher electric and/or magnetic fields and

childhood leukemia risk, but that we had diminished ability to find an association with measured fields because of a methodological bias, most likely measurement error. Although we measured magnetic fields over 24 hours or more, in contrast to the spot measurements in the study of Savitz et al., even the 24-hour measurements may be a poor approximation of the average long-term exposure. Although magnetic fields are imperfectly approximated by wiring configuration (16), the wiring configuration is determined with little error, is unlikely to change over time within a residence, and therefore, may actually be a superior indication of long-term field exposure than are the measurements taken.

Another possibility is that we did not measure the biologically relevant aspect of electric and magnetic fields in relation to leukemia risk. Biologic effects of electric and magnetic fields relevant to potential carcinogenesis have not been well-studied. Perhaps average exposure or the peak exposure are not the parameters of real interest, but some other attribute, such as abrupt changes in the field, is important.

In addition, carcinogenic effects of magnetic fields might not be a simple function of dose. For example, the magnetic field-induced calcium-ion efflux from chicken brain tissue depends on the static magnetic field (17), as well as the frequency (18) and the direction (19) of the oscillating magnetic field. Whether calcium efflux per se is related to carcinogenesis is unknown. However, this experimental evidence highlights the possibility that we are looking at the wrong measure of electric and magnetic field exposure.

Selection bias might theoretically explain the apparent lack of an association with measured fields. Whereas we obtained wiring maps on virtually all subjects, a smaller percentage granted permission for us to make measurements in the home. If non-participation in the measurements were related both to electric and magnetic field exposure and case-control status, a true association with measured electric and magnetic fields might have been missed. However, the magnetic field predicted from wir-

ing characteristics was similar in the homes in which we made measurements and in those in which we did not, and therefore, selection bias by this mechanism is unlikely to have occurred.

A second interpretation of the data is that there is no true association between electric and magnetic fields and leukemia risk. Then the lack of a consistent association between field measurements and leukemia risk would reflect the truth, and the observed association between leukemia risk and Denver Wertheimer-Leeper wiring configuration classification would be due to bias.

The use of random digit dialing to identify controls may have introduced selection bias in our study and that of Savitz et al. (2). We made a large number of telephone calls to reach one eligible control and cannot assess whether our ability to reach potential subjects might be related to their wiring configurations, producing an artifactual association between wiring configuration and leukemia risk. However, in the first study of childhood cancer risk in relation to electric and magnetic field exposure (1), the control selection mechanism was less subject to selection bias, and the data allowed assessment of whether it had occurred. The similarity of wiring configuration classification between subjects who were traced and those who were not makes selection bias improbable in that study.

Confounding might possibly explain the association between wiring configuration and leukemia risk observed in this study and others. However, adjustment for a wide variety of factors thought to influence leukemia risk did not substantially influence the results. Unfortunately, there is little known about the etiology of childhood cancer, and therefore, confounding by a factor not known to be a disease risk is possible. Yet such a factor would need to be strongly associated with risk or extremely tightly correlated with wiring configuration classification to have produced the odds ratios in our study and others.

The Denver Wertheimer-Leeper configuration classification scheme was developed specifically to approximate residential mag-

netic fields in Denver. Characteristics of the power distribution differ between Los Angeles and Denver. We examined the use of Wye versus Delta primary distribution lines because Los Angeles is characterized by the more frequent use of Delta primary distribution lines, but found no relation to risk. Likewise, fields estimated from wiring characteristics by the method of Kaune et al. (10) were not associated with risk. It would be of interest to develop a wiring configuration classification based on empiric and theoretical considerations specifically for Los Angeles that would be superior to the Denver Wertheimer-Leeper classification as a predictor of fields. If the improved wiring configuration classification were more closely associated with risk than the Denver Wertheimer-Leeper scheme, this would provide strong evidence that the association with Denver Wertheimer-Leeper wiring configuration classification reflects an underlying association with the magnetic field rather than bias.

Our results, along with most previous data, support an association between wiring configuration and childhood leukemia risk. However, we did not find a clear association with measured magnetic or electric fields. Future work incorporating evolving experimental knowledge on the biologic effects of electric and magnetic fields might help to highlight the aspect of the fields most likely to relate to childhood leukemia risk. Improved assessment of exposure would help to determine whether the lack of an association simply reflects measurement error. In addition, restriction of studies to areas where participation rates tend to be high and the assessment of wiring configurations on all potential subjects would help to minimize the possibility of selection bias and aid in the interpretation of future data.

REFERENCES

1. Wertheimer N, Leeper E. Electrical wiring configurations and childhood cancer. *Am J Epidemiol* 1979;109:273-84.
2. Savitz DA, Wachtel H, Barnes FA, et al. Case-control study of childhood cancer and exposure to 60-Hz magnetic fields. *Am J Epidemiol* 1988;128:21-38.
3. Coleman MP, Bell CMJ, Taylor H-L, et al. Leukaemia and residence near electricity transmission equipment: a case-control study. *Br J Cancer* 1989;60:793-8.
4. Fulton JP, Cobb S, Preble L, et al. Electrical wiring configurations and childhood leukemia in Rhode Island. *Am J Epidemiol* 1980;111:292-6.
5. Tomenius L. 50-Hz electromagnetic environment and the incidence of childhood tumors in Stockholm County. *Bioelectromagnetics* 1986;7:191-207.
6. Savitz DA, John EM, Kleckner RC. Magnetic field exposure from electric appliances and childhood cancer. *Am J Epidemiol* 1990;131:763-73.
7. Lowengart RA, Peters JM, Cicioni C, et al. Childhood leukemia and parents' occupational and home exposures. *J Natl Cancer Inst* 1987;79:39-46.
8. Hisserich J, Martin SP, Henderson BE. An area-wide cancer reporting network. *Public Health Rep* 1975;90:15-17.
9. Mack TM. Cancer surveillance program in Los Angeles County. *Natl Cancer Inst Monogr* 1977;47:99-101.
10. Kaune WT, Stevens RG, Callahan NJ, et al. Residential magnetic and electric fields. *Bioelectromagnetics* 1987;8:315-35.
11. Wertheimer N, Leeper E. Adult cancer related to electrical wires near the home. *Int J Epidemiol* 1982;11:345-55.
12. Barnes F, Wachtel H, Savitz D, et al. Use of wiring configuration and wiring codes for estimating externally generated electric and magnetic fields. *Bioelectromagnetics* 1989;10:13-21.
13. SAS Institute, Inc. SAS procedures guide. Release 6.03 ed. Cary, NC: SAS Institute, Inc., 1988.
14. Breslow NE, Day NE. Statistical methods in cancer research. Vol 1. The analysis of case-control studies. (IARC scientific publication no. 32). Lyon, France: International Agency for Research on Cancer, 1980.
15. Wertheimer N, Leeper E. Re: "Electrical wiring configurations and childhood leukemia in Rhode Island." (Letter). *Am J Epidemiol* 1980;111:461-2.
16. Keam DW. Wire coding configurations are poor surrogates for magnetic field exposures. *Radiat Protection Aust* 1988;6:82-6.
17. Blackman CF, Benane SG, Rabinowitz JR, et al. A role for the magnetic field in the radiation-induced efflux of calcium ions from the brain tissue in vitro. *Bioelectromagnetics* 1985;6:327-37.
18. Blackman CF, Benane SG, Elliot DJ, et al. Influence of electromagnetic fields on the efflux of calcium-ions from brain tissue in vitro: a three model analysis consistent with the frequency response up to 510 Hz. *Bioelectromagnetics* 1988;9:215-27.
19. Blackman CF, Benane SG, House DE, et al. Importance of alignment between local DC magnetic field and an oscillating magnetic field in responses of brain tissue in vitro and in vivo. *Bioelectromagnetics* 1990;11:159-67.