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# Original Contributions

## ACUTE NONLYMPHOCYTIC LEUKEMIA AND RESIDENTIAL EXPOSURE TO POWER FREQUENCY MAGNETIC FIELDS[1]

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**Recent research has suggested that nonionizing radiation in the form of power-frequency magnetic fields may play some role in carcinogenesis in general and in acute nonlymphocytic leukemia in particular. Much of the epidemiologic evidence is preliminary in nature and the methods of previous studies have been criticized. In order to further evaluate this hypothesis, a population-based case-control study of adult acute nonlymphocytic leukemia and residential exposure to power-frequency magnetic fields was carried out in western Washington state. Analyses were based on 114 cases who were newly diagnosed from 1981 to 1984 and identified from a population-based cancer registry, and 133 controls who were chosen from the study area by random digit dialing. Magnetic field exposure was estimated from external electrical wiring configurations within 140 ft (42.7 m) of each subject's residence. In addition, magnetic fields were measured inside the subject's residence at the time of interview. Neither the directly measured magnetic fields nor the surrogate values based on the wiring configurations were associated with acute nonlymphocytic leukemia.**

**electromagnetic fields; leukemia**

Although there has been much research into the causes of acute nonlymphocytic leukemia, the etiology of the majority of cases remains unknown. While ionizing radiation (1–5), benzene (6–10), and alkylating agents (11–15) may all bear a causal relation to acute nonlymphocytic leukemia, exposures to these three agents account for only a small fraction of the cases. Although the evidence is weak, preliminary research has suggested that nonionizing radiation in the form of power-frequency magnetic fields may play a role in carcinogenesis.

Magnetic fields have been shown to affect the behavior of animals (16, 17). In addition, there is some evidence that ex-

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posure to magnetic fields may affect biologic development. Research on experimental animals has shown that magnetic fields may affect morphogenesis (18), growth rate (19), response rate (20), tissue respiration rate (21), and peripheral blood cells (22). To our knowledge, there have been no studies to date which suggest that magnetic fields affect carcinogenesis in laboratory animals. Research on humans has shown that magnetic fields aid in fracture healing (23).

The magnetic field frequencies examined in experiments are varied and widely spaced across the electromagnetic spectrum. On the other hand, epidemiologic studies have focused on power-frequency (50–60 Hertz) magnetic fields. Since 1979, when Wertheimer and Leeper (24) first reported an association between residential electrical wiring configurations and childhood cancer in Colorado, controversy has surrounded the hypothesis that power-frequency magnetic fields might play a role in human carcinogenesis. In a second study of adult cancers, Wertheimer and Leeper (25) reported similar results and heightened the controversy. In both studies, an increased risk was reported for all cancers combined. An increased risk for all leukemias combined was not found in the adult study but was found in the childhood study. Although it was not specifically stated, most of these childhood leukemias are presumably of the acute lymphocytic variety. Although these studies have been criticized (26, 27), their results have not been firmly refuted by subsequent investigations.

Additional case-control studies have reported increased risks of childhood cancer (28), brain cancer (29), and acute myelocytic leukemia (30, 31) associated with exposure to power-frequency magnetic fields. Another case-control study reported no increased risks for childhood leukemia (32). Results from three cohort studies are inconsistent—two such studies (33, 34) reported no increased risk for all cancers combined, and the other cohort study (35) reported an overall increase in cancer risk. Some evidence that suggests an association between magnetic fields and leukemia has been found in studies of occupational exposures (36–42). Based on proportional analyses, increased risks have been reported for acute myelocytic leukemia (36–39) and all acute leukemias combined (40–42).

When considered on an individual basis, the above studies may not be convincing. However, when viewed as a whole, enough evidence exists to suggest that further investigation is warranted. This paper reports the results of a population-based case-control study of adult acute nonlymphocytic leukemia and residential exposure to power-frequency magnetic fields conducted in western Washington state. Largely because of the suggestion from the occupational studies that magnetic field exposure might result in increased risk of acute myelocytic leukemia, acute nonlymphocytic leukemia, which includes acute myelocytic leukemia, was selected for study. In addition to attempting to replicate Wertheimer and Leeper's assessment of exposure based on maps of external wiring configurations, in-house magnetic field measurements were made to evaluate possible relations between 60 Hz magnetic fields and acute nonlymphocytic leukemia.

## MATERIALS AND METHODS

Cases of acute nonlymphocytic leukemia were identified through the Cancer Surveillance System of the Fred Hutchinson Cancer Research Center. The Cancer Surveillance System is a population-based cancer registry funded by the National Cancer Institute as part of the Surveillance, Epidemiology, and End Results (SEER) program (43). The present study was restricted to those cases of acute nonlymphocytic leukemia that occurred in residents of King, Pierce, or Snohomish Counties who were aged 20–79 years at diagnosis and who were newly diagnosed during the period January 1, 1981 to December 31, 1984. Both living and deceased cases were included. The cases were further restricted to those with one of the histologic types (44) shown in table 1.

TABLE 1

*Number of cases of acute nonlymphocytic leukemia by histologic classification, western Washington state, 1981–1984*

| ICD-O* code | Description | No. interviewed |
|---|---|---|
| 9840 | Erythroleukemia | 5 |
| 9841 | Acute erythremia | 1 |
| 9861 | Acute myeloid leukemia | 91 |
| 9862 | Subacute myeloid leukemia | 2 |
| 9866 | Acute promyelocytic leukemia | 5 |
| 9891 | Acute monocytic leukemia | 9 |
| 9910 | Megakaryocytic leukemia | 1 |
| | Total | 114 |

* ICD-O, *International Classification of Diseases for Oncology* (44).

The control group was selected from the same three-county area as the cases by using a random digit dialing scheme based on the method described by Waksberg (45). Controls were frequency matched to the cases by sex and age (five-year groups: 20–24, 25–29, . . . , 75–79 years). Approximately one living control per case was chosen.

All study subjects or their next-of-kin were interviewed in person at a time and location of their choice by one of two interviewers specifically trained to administer the questionnaire. Topics covered included a complete residence history, electric appliance usage, occupational history, ionizing radiation exposures, medical history, medications and drugs consumed, smoking and alcohol history, pet ownership, and demographics. In order to make the period of recall as similar as possible between cases and controls, an arbitrary reference date was randomly assigned to each control, in such a manner that the reference dates were uniformly distributed over the period of time during which the cases were diagnosed.

Three separate means of exposure assessment were used in this study.

1) External electrical wiring configurations within 140 ft (42.7 m) of each subject's residence were mapped. This was done to repeat and extend the methods of Wertheimer and Leeper (25), classifying these wiring configurations according to the subject's potential exposure to power-frequency magnetic fields.

2) One-time-only magnetic field measurements were made in eligible residences by the interviewers during the in-house interview.

3) Magnetic field measurements were recorded over a 24-hour period in a limited sample of the residences in which the interviewers had initially completed one-time-only measurements.

All addresses for single family residences, mobile homes, duplexes, or triplexes that were located in the study area and were occupied by the subject within 15 years prior to the reference date were identified from the interviews. These residences were assigned to a technician who drew a scale map of all outdoor electrical power equipment, including all transmission and distribution lines, transformers, service drops, and any other electrical constructions that were located within 140 ft (42.7 m) of the residence. The technician was "blinded" as to the case/control status of each assigned address. Based on these maps, the association between exposures based on Wertheimer and Leeper's wiring classification scheme (25) and the risk of acute nonlymphocytic leukemia was evaluated. This scheme ranks residences on their potential for 60 Hz magnetic field exposure based on the geographic proximity and current carrying capacity of the electric power distribution wires around the residences. The four categories (in order of increasing potential for exposure) are endpoles, ordinary low current configurations, ordinary high current configurations, and very high current configurations.

In addition to the Wertheimer and Leeper exposure assessment scheme, Kaune et al. (46) have developed another exposure assessment scheme based on an analysis of the relation between the 24-hour measurements and the maps for the same residences. This scheme was derived from a correlational analysis of various aspects of the wiring configurations with the 24-hour meter readings made in the sampled residences. Based on this scheme, a magnetic field level inside each residence was estimated from the wiring configuration map of that residence. Briefly, the magnetic field was found to be proportional to the number

of electric service drops to other buildings within 140 ft (42.7 m) of the residence, the number of phases (wires) associated with the primary power distribution system closest to the residence, and the inverse distance from the residence to any high voltage power transmission lines within 140 ft (42.7 m) of the residence.

If the in-person interview was completed in the residence where the subject had lived for one continuous year or longer immediately prior to the reference date, the interviewer made one-time-only measurements of the 60 Hz magnetic fields both inside and outside the residence. All readings were made on a Power-Frequency Field Meter Model 111 (Electric Field Measurements, Inc., West Stockbridge, MA). Each meter was subject to the following checks: simple daily performance checks by the interviewers, weekly calibrations at the Fred Hutchinson Cancer Research Center, and semiannual absolute calibrations at Battelle Pacific Northwest Laboratories.

Measurements were made in the kitchen, the subject's bedroom, and the family gathering room. Before the measurements were taken, the interviewer and respondent went through the residence and turned off all appliances that could conveniently be switched off, including lights, kitchen appliances, washer, dryer, radio, stereo, television, and furnace (if possible, by reducing the thermostat setting). Several major appliances were not adjusted, including the refrigerator, freezer, hot water heater, and any other similar appliances which the interviewer felt might be overly disruptive to the household. After the appliances were turned off, the residence was considered to be in a "low power" configuration. At this point, magnetic field measurements were made in the three rooms indicated above.

After these low power measurements were made, each of the three rooms was measured in a "high power" configuration. A high power configuration was defined as a state where all the electrical appliances such as lights, televisions, radios, and sound systems were turned on in the bedroom and family gathering room, and where the appliances were turned on in the kitchen so as to simulate a situation when large amounts of cooking and baking were being done (e.g., for a party or big family celebration). "High power" measurements were made in each room while only that room was in a high power configuration, i.e., the rest of the house was in a low power configuration.

Since magnetic fields are vectors (having both magnitude and direction), they were calculated as the root mean square (rms) of three field measurements made at right angles by the interviewers. For example, let $X$ = the first horizontal component of the rms magnetic field; $Y$ = the second horizontal component of the rms magnetic field (perpendicular to $X$); and $Z$ = the vertical component of the rms magnetic field (perpendicular to both $X$ and $Y$). Then

$$\text{rms} = [X^2 + Y^2 + Z^2]^{1/2}$$

Although the choice of units is arbitrary, the magnetic field was expressed in milligauss.

Two simple exposure quantities were calculated for the low power magnetic field measurements: 1) the mean of the three-room measurements; and 2) the mean of the three-room measurements weighted by time spent by the subject in each room. Similar calculations were made for the high power magnetic field measurements.

The analysis included the calculation of crude odds ratios from unstratified 2 × 2 tables. Acute nonlymphocytic leukemia risks were also estimated by fitting a logistic regression model (47), which allows for the calculation of the risk associated with each independent variable. A variable expressing exposure to residential 60 Hz magnetic fields (defined by surrogate measures from wiring configurations or by actual measured values) was always included as a predictor variable in the model.

## RESULTS

### *Basic characteristics of cases and controls*

Table 2 shows the number of eligible and interviewed subjects. Failure to interview

TABLE 2

*Number of acute nonlymphocytic leukemia cases and controls eligible for study, interviewed, and not interviewed (by reason for nonparticipation), western Washington state, 1981–1984*

| Status | Cases | | Controls | |
|---|---|---|---|---|
| | No. | % | No. | % |
| Identified as eligible | 164 | 100.0 | 204 | 100.0 |
| Not interviewed | | | | |
| Physician refusal | 28 | 17.1 | NA* | |
| Subject refusal | 8 | 4.9 | 55 | 27.0 |
| Moved/unable to locate | 6 | 3.7 | 7 | 3.4 |
| Too ill to complete interview | 0 | 0 | 8 | 3.9 |
| Noncooperating hospital | 6 | 3.7 | NA* | |
| Other reasons for incompletion | 2 | 1.2 | 1 | 0.5 |
| Total interviewed | 114 | 69.5 | 133 | 65.2 |

* NA, not applicable.

cases was due primarily to physician refusal (17.1 per cent). In 25 (89.3 per cent) of the 28 physician refusals, the subject was deceased. Failure to interview controls was due primarily to subject refusal (27.0 per cent). The final roster for analysis included 114 cases and 133 controls. Of the 114 cases, nine were monocytic, six were erythrocytic, one was megakaryoctic, and 98 were myelocytic. There were no significant differences between the interviewed and uninterviewed subjects by age or sex. We completed a residential map on 36 (72.0 per cent) of the uninterviewed cases and 43 (60.6 per cent) of the uninterviewed controls. These subjects were included in some of the simpler analyses described below.

Table 3 compares the cases and controls by various demographic factors. The cases tended to be of lower socioeconomic status than the controls as measured by family income ($p = 0.03$) and education ($p = 0.16$). Also, more cases than controls were cigarette smokers ($p = 0.04$). This difference in cigarette smoking has potential etiologic significance (48) and is extensively evaluated elsewhere (49). No other significant differences between the cases and controls were noted.

TABLE 3

*Number of acute nonlymphocytic leukemia cases and controls, by selected demographic factors, western Washington state, 1981–1984*

| Demographic factor | Cases | | Controls | |
|---|---|---|---|---|
| | No. | % | No. | % |
| Age (years) | | | | |
| 20–39 | 21 | 18.4 | 26 | 19.5 |
| 40–59 | 27 | 23.7 | 38 | 28.6 |
| 60–79 | 66 | 57.9 | 69 | 51.9 |
| Sex | | | | |
| Male | 69 | 60.5 | 69 | 51.9 |
| Female | 45 | 39.5 | 64 | 48.1 |
| Marital status | | | | |
| Married or living as married | 80 | 70.2 | 88 | 66.2 |
| Widowed | 17 | 14.9 | 18 | 13.5 |
| Divorced | 11 | 9.6 | 15 | 11.3 |
| Never married | 6 | 5.3 | 12 | 9.0 |
| Race | | | | |
| White | 104 | 91.2 | 129 | 97.0 |
| Nonwhite | 10 | 8.8 | 4 | 3.0 |
| Educational level (grade) | | | | |
| Less than high school (0–11) | 27 | 23.7 | 22 | 16.5 |
| High school graduate (12–15) | 63 | 55.3 | 76 | 57.1 |
| College graduate (16+) | 20 | 17.5 | 35 | 26.3 |
| Unknown | 4 | 3.5 | 0 | 0 |
| Combined family income | | | | |
| 0–$15,000 | 47 | 41.2 | 39 | 29.3 |
| $15,000–$30,000 | 41 | 36.0 | 46 | 34.6 |
| $30,000–$45,000 | 12 | 10.5 | 25 | 18.8 |
| $45,000+ | 8 | 7.0 | 20 | 15.0 |
| Refused or unknown | 6 | 5.3 | 3 | 2.3 |
| Cigarette smoking | | | | |
| Never | 32 | 28.1 | 54 | 40.6 |
| Present or past smoker | 82 | 71.9 | 79 | 59.4 |

In some studies (50, 51), there has been a suggestion that pet owners (especially owners of sick pets) may be at increased risk of leukemia, but other studies (52–55) have failed to support this hypothesis. In the present study, we found no significant relation between acute nonlymphocytic leukemia and prior ownership of a dog, cat, or bird that had died of cancer or any blood disease diagnosed by a veterinarian.

We also found no significantly increased risk for people with exposure to ionizing radiation. This included radiation from

various medical procedures and from occupational exposures, as well as any other radiation exposures that the subject had encountered.

*Wiring configurations coded by Wertheimer and Leeper's scheme (25)*

Table 4 shows the total number of years of residence in dwellings for which wiring configuration maps were made. The overall distribution of the controls was very similar to that of the cases. Because some subjects had lived in apartments for all of the 15 years prior to the reference date, or had moved into the study area immediately prior to their reference date, no maps were completed on 14.9 per cent of the interviewed cases and 12.8 per cent of the interviewed controls.

TABLE 4

*Number of acute nonlymphocytic leukemia cases and controls for which residential wiring configuration maps were made, by total number of years of residence in mapped dwellings during the 15 years prior to the reference date, western Washington state, 1981–1984*

| No. of years | Cases | | Controls | |
|---|---|---|---|---|
| | No. | % | No. | % |
| 0 | 17 | 14.9 | 17 | 12.8 |
| 1–4 | 11 | 9.6 | 7 | 5.3 |
| 5–9 | 11 | 9.6 | 19 | 14.3 |
| 10–15 | 24 | 21.1 | 35 | 26.3 |
| 16 | 51 | 44.7 | 55 | 41.4 |
| Total | 114 | 100.0 | 133 | 100.0 |

We attempted to duplicate as closely as possible the analysis done by Wertheimer and Leeper (25). This analysis was based on the mapped residence at which the subject had spent the longest period of time 3–10 years prior to the reference date. The upper part of table 5 shows the results of fitting a logistic model to the data. There is no evidence of an increased risk associated with higher current configurations as assessed using this scheme. Relative risk estimates based on a stratified analysis were similar to those from the logistic analysis. This analysis was repeated excluding those subjects with underground wiring (coded as endpoles) and similar results were found.

If power-frequency magnetic fields do affect carcinogenesis, they may play a role as a promoter (56). Relative risk was therefore assessed in relation to wiring configurations of the residence closest to the reference date. The lower half of table 5 shows the results of this analysis. When the exposures for the mapped residences of the uninterviewed subjects were included in the analysis, the risk estimates were similar and, again, there was no evidence of an increased risk associated with higher current configurations.

TABLE 5

*Risk estimates of acute nonlymphocytic leukemia in relation to exposure based on Wertheimer and Leeper's wiring classification scheme (25) from fitted logistic regression models, western Washington state, 1981–1984*

| Electrical wiring configuration | No. of cases | No. of controls | Odds ratio* | 95% CI† |
|---|---|---|---|---|
| Longest residence 3–10 years before reference date | | | | |
| Very low (end pole) | 42 | 44 | 1.00 | |
| Ordinary low | 21 | 37 | 0.60 | 0.29–1.22 |
| Ordinary high | 21 | 23 | 0.77 | 0.35–1.68 |
| Very high | 5 | 6 | 0.79 | 0.22–2.89 |
| Residence closest to reference date | | | | |
| Very low (end pole) | 42 | 52 | 1.00 | |
| Ordinary low | 26 | 38 | 0.81 | 0.41–1.61 |
| Ordinary high | 24 | 19 | 1.36 | 0.62–2.96 |
| Very high | 5 | 7 | 0.84 | 0.24–2.93 |

* Controlling for age, sex, cigarette smoking, family income, and race.

† CI, confidence interval.

*Wiring configurations coded by Kaune et al.'s scheme (46)*

Table 6 shows the risk estimates for the Kaune et al. exposure estimates categorized into low exposure (0–0.50 milligauss), medium exposure (0.51–1.99 milligauss), and high exposure (2.00+ milligauss). The upper portion of the table presents the odds ratios for the residences in which the subjects had lived the longest 3–10 years prior to the reference date, while the lower portion of the table shows those for the residences closest to the reference dates. There is no evidence that increased exposure is associated with increased risk in either portion of the table. These exposures were also categorized into tertiles and all the risk estimates (not shown) were not significantly different from unity and no dose-response was observed.

Since this exposure variable was measured on a continuous scale, a logistic model was fitted to the data. A value of one for the exposure variable (based on the longest residence 3–10 years prior to the reference date) was defined as a 0.1 milligauss expected magnetic field for the Kaune et al. code. While controlling for age, sex, cigarette smoking, family income, and race, the parameter estimate for the exposure variable was −0.0093, which suggests that the estimated relative risk decreases somewhat as the exposure increases. From this estimate, one can calculate the odds ratio of exposure to a 2 milligauss field versus no exposure as $e^{(20)(-0.0093)} = 0.83$ (95 per cent confidence interval (CI) = 0.40–2.09).

*Field measurements made by the interviewers*

A large proportion of our study subjects (or their next-of-kin) had moved after the reference date. Because of this, we completed measurements for 138 (55.9 per cent) of our interviewed subjects. All measurements were made in milligauss and were adjusted for season of year and time of day.

Our data suggest that the use of household appliances may make a small contribution to the magnetic environment in the residence. Based on all 138 measured residences in this study, it was found that the mean low power configuration magnetic field was 0.929 milligauss. The mean high power configuration magnetic field was 1.105 milligauss. The mean difference between the high and low power measurements was 0.174 milligauss, and this difference was statistically significant ($p < 0.001$) on the basis of a $t$ test ($t = 3.58$, 137 degrees of freedom).

Table 7 shows the risk estimates for exposure under conditions of low and high

TABLE 6

*Risk estimates of acute nonlymphocytic leukemia in relation to Kaune et al.'s residential exposure classification (46), western Washington state, 1981–1984*

| Exposure level (milligauss) | No. of cases | No. of controls | Odds ratio | 95% CI* |
|---|---|---|---|---|
| Longest residence 3–10 years before reference date | | | | |
| 0–0.50 | 29 | 28 | 1.00 | |
| 0.51–1.99 | 46 | 64 | 0.69 | 0.37–1.32 |
| 2.00+ | 14 | 18 | 0.75 | 0.31–1.80 |
| Residence closest to reference date | | | | |
| 0–0.50 | 40 | 42 | 1.00 | |
| 0.51–1.99 | 70 | 92 | 0.80 | 0.47–1.36 |
| 2.00+ | 23 | 25 | 0.97 | 0.47–1.98 |

* CI, confidence interval.

TABLE 7

*Risk estimates of acute nonlymphocytic leukemia in relation to the weighted and unweighted mean magnetic field measurements made in the kitchen, bedroom, and family gathering room of the subject's residence at reference date, western Washington state, 1981–1984*

| Exposure level (milligauss) | Odds ratio (95% CI*) | |
|---|---|---|
| | Lower power configuration | High power configuration |
| Mean exposure | | |
| 0–0.50 | 1.00 | 1.00 |
| 0.51–1.99 | 1.16 (0.52–2.56) | 0.55 (0.25–1.22) |
| 2.00+ | 1.50 (0.48–4.69) | 1.56 (0.49–5.04) |
| Weighted mean exposure | | |
| 0–0.50 | 1.00 | 1.00 |
| 0.51–1.99 | 1.17 (0.54–2.54) | 0.91 (0.42–1.96) |
| 2.00+ | 1.03 (0.33–3.20) | 1.25 (0.35–4.48) |

* CI, confidence interval.

power configurations. We calculated both the mean exposure (the mean of the kitchen, bedroom, and family room magnetic field measurements) and the weighted mean exposure (weighted by the relative amount of time the subject spent in each of the three rooms). Each exposure was categorized into fixed categories (0–0.50 milligauss, 0.51–1.99 milligauss, and 2+ milligauss). An increase in risk was associated only with the low power measurements of magnetic field exposure, and this apparent trend could easily be due to chance (trend test, $p = 0.50$). This trend was further investigated by considering subjects with 3+ milligauss exposure (very high exposure) versus those with 0–0.50 milligauss exposure (low exposure). The odds ratio was 0.94 (95 per cent CI = 0.16–5.54). These exposures were also categorized into tertiles and the risk estimates were not significantly different from unity and no dose-response was observed (not shown).

Four separate logistic models were fitted to the data with the four exposures shown in table 7 evaluated on a continuous scale while controlling for age, sex, race, family income, and cigarette smoking. Each exposure coefficient was close to 0, suggesting that the measured fields were not appreciably associated with acute nonlymphocytic leukemia risk. The logistic risk estimate of a 2 milligauss field exposure versus no exposure for the low power exposure was 1.30 (95 per cent CI = 0.56–3.00), comparable to the risk estimate of 1.50 from the categorical analysis. The logistic risk estimate for the weighted mean exposure of 2 milligauss was 0.96 (95 per cent CI = 0.37–2.47), comparable to 1.03 from the categorical analysis.

### *Electric blankets*

Besides the ambient magnetic fields found in the residence, it is possible that substantial additional exposure may come from the use of electric blankets. There is some evidence that the fields generated by electric blankets are relatively intense (25). In addition, they may be in continuous use for extended periods of time, and the user tends to be in close proximity to the blanket while it is on. The use of electric blankets, electric water bed heaters, and electric mattress pads was evaluated in our data, and no significant associations were found. There was a nonsignificantly increased risk associated with the use of electric blankets that was limited only to those subjects with a family income less than $15,000 per year (odds ratio = 2.40, 95 per cent CI = 0.99–5.84). However, this association was not observed in those subjects with a higher income (odds ratio = 1.01, 95 per cent CI = 0.53–1.94).

## Discussion

There was no consistent evidence of an increased risk of acute nonlymphocytic leukemia associated with residential exposure to power-frequency magnetic fields. None of the risk estimates were significantly greater than 1.0, and no convincing dose-response relation was observed for the various measures of exposure that were considered in this study.

This study has several inherent limitations.

First, the estimates of exposure based on the wiring configurations were indirect. An analysis of the relation between the 24-hour magnetic fields measurements and the Wertheimer and Leeper code (25) resulted in a correlation coefficient of 0.41 (46), which suggests that there is a relation between the two variables. However, only 17 per cent of the variation in the magnetic field measurements is explained by the Wertheimer code, so this index of exposure is imprecise. This would reduce the power of this study to detect a true association between acute nonlymphocytic leukemia and magnetic field exposure utilizing the Wertheimer code as an index of exposure.

Second, the direct field measurements were made after the reference date. Even though there is no direct evidence that power-frequency magnetic fields change on the average from year to year, neither are there any data to suggest that these fields

remain stable over long periods. It may be impossible to obtain exact historical measures of this type of exposure in a retrospective study.

Third, only residential exposures were considered. Other (possibly substantial) power-frequency magnetic field exposures from other settings (such as place of employment) were not studied.

Fourth, the comparison of information from next-of-kin respondents for deceased cases with information from live controls may introduce some bias into a case-control study (57). This is probably not true for this study, however, since exposure assessment was based on residence histories which, in another study from the same area (58), were as reliably obtained from next-of-kin as from live subjects for a 30-year period. The vital status of the subject would not affect the mapping of power lines around the residence or the reading of field meters. In addition, no significant differences were found between the deceased and living cases.

To balance these limitations, the study has a number of strengths. Use of a population-based cancer registry for case identification allowed identification of virtually all cases of cancer that occurred in the study area. Moreover, we were able to select the controls from the same population that contributed the cases. These procedures minimized the potential for selection bias to influence the results of the study. Unlike most previous epidemiologic studies of power-frequency magnetic field exposure and neoplasia, actual in-house magnetic field measurements were made and analyzed. In addition, the mapping technician was unaware of the subject status, as were the investigators from Battelle Pacific Northwest Laboratories who assigned both the Wertheimer and Leeper and the Kaune et al. codes for each residence from the maps. Also, the Kaune et al. code was based on correlations between wiring configurations and actual measurements of magnetic fields. Finally, data on potentially confounding factors were obtained through a personal interview. This allowed for the control of these factors on an individual level when estimating relative risks in relation to magnetic field exposure.

The sample size of the current study was such that a twofold increase in risk from exposure to high current configurations in the longest residence 3–10 years before the reference date could be rejected with 95 per cent confidence. Due to the smaller sample size, the confidence intervals for the relative risks are wider in relation to the field measurements, and, as such, caution is advised in evaluating this part of the study. However, the absence of an increase in risk with level of exposure as judged by these measurements provides some additional evidence against an association between exposure and the disease under study.

The results of this study thus do not provide evidence for an association between residential exposure to 60 Hz magnetic fields and acute nonlymphocytic leukemia. None of the exposure measurements made in this study were associated with acute nonlymphocytic leukemia. There was no evidence that recent exposure had a promotional effect on acute nonlymphocytic leukemia. This study is consistent with the study by Wertheimer and Leeper (25) in that neither study reported an increased risk of leukemia associated with exposure to residential magnetic fields. Since this study was limited to acute nonlymphocytic leukemia, magnetic fields may be associated with neoplasms other than acute nonlymphocytic leukemia.

If future studies of magnetic field exposure are undertaken, exposure measurements might be improved in two ways. First, in-house measurements could be extended over time. This would involve taking measurements over a 24-hour period (or longer if possible) for all study subjects. These measurements could then be repeated several times in different seasons of the year. Second, exposure measurements could be extended to include nonresidential settings such as the subject's place of employment, although meters and other bulky

equipment may not always be welcome in occupational settings. Efforts are underway to develop convenient personal exposure monitors for magnetic fields (59). If these monitors become available and feasible for personal monitoring, they could be useful in future epidemiologic studies.

## References


1. Bizzozzero OJ, Johnson KG, Ciocco A. Radiation-related leukemia in Hiroshima and Nagasaki, 1946–64. I. Distribution, incidence and appearance time. N Engl J Med 1966;274:1095–1101.
2. Bizzozzero OJ, Johnson KG, Ciocco A, et al. Radiation-related leukemia in Hiroshima and Nagasaki, 1946–64. II. Observations on type specific leukemia, survivorship and clinical behavior. Ann Intern Med 1967;66:522–30.
3. Seltser R, Sartwell PE. The influence of occupational exposure to radiation on the mortality of American radiologists and other medical specialists. Am J Epidemiol 1965;81:2–22.
4. Greene MH, Young RC, Merrill JM, et al. Evidence of a treatment dose response in acute nonlymphocytic leukemias which occur after therapy of non-Hodgkin's lymphoma. Cancer Res 1983; 43:1891–8.
5. Smith PG, Doll R. Mortality among patients with ankylosing spondylitis after a single treatment course with x rays. Br Med J 1982;284:449–60.
6. Vigliani EC, Forni A. Benzene and leukemia. Environ Res 1976;11:122–7.
7. Brandt L, Nilsson PG, Mitelman F. Non-industrial exposure to benzene as leukaemogenic risk factor. (Letter.) Lancet 1977;2:1074.
8. Infante PF, Rinsky RA, Wagoner JK, et al. Leukaemia in benzene workers. Lancet 1977;2:76–8.
9. Greene MH, Hoover RN, Eck RL, et al. Cancer mortality among printing plant workers. Environ Res 1979;20:66–73.
10. Ott MG, Townsend JC, Fishback WA, et al. Mortality among individuals occupationally exposed to benzene. Arch Environ Health 1978;33:3–10.
11. Greene MH, Boice JD, Greer BE, et al. Acute nonlymphocytic leukemia after therapy with alkylating agents for ovarian cancer: a study of five randomized clinical trials. N Engl J Med 1982;307:1416–21.
12. Reimer RR, Hoover R, Fraumeni JF, et al. Acute leukemia after alkylating-agent therapy of ovarian cancer. N Engl J Med 1977;297:177–81.
13. Berk PD, Goldberg JD, Silverstein MN, et al. Increased incidence of acute leukemia in polycythemia vera associated with chlorambucil therapy. N Engl J Med 1981;304:441–7.
14. Bartolucci AA, Liu C, Durant JR, et al. Acute myelogenous leukemia as a second malignant neoplasm following successful treatment of advanced Hodgkin's disease. Cancer 1983;52:2209–13.
15. Curtis RE, Hankey BF, Myers MH, et al. Risk of leukemia associated with first course of cancer treatment: an analysis of the Surveillance, Epidemiology, and End Results Program experience. JNCI 1984;72:531–44.
16. Phillips JB. Two magnetoreception pathways in a migratory salamander. Science 1986;233:765–7.
17. Blakemore RP, Frankel RB, Wolfe RS. Ferromagnetism in freshwater bacteria. In: Philips RD, Gillis MG, Kaune WT, et al., eds. Biological effects of extremely low frequency electromagnetic fields. Proceedings of the Eighteenth Annual Hanford Life Sciences Symposium. DOE Symposium Series 50, CONF-781016, 1979:400–7.
18. Delgado JMR, Leal J, Monteagudo JL, et al. Embryological changes induced by weak, extremely low frequency electromagnetic fields. J Anat 1982;134:533–51.
19. Greenbaum B, Goodman EM, Marron MT. Magnetic field effects on mitotic cycle length in physarum. Eur J Cell Biol 1982;27:156–60.
20. Persinger MA, Pear JJ. Prenatal exposure to an ELF-rotating magnetic field and subsequent increase in conditioned suppression. Dev Psychobiol 1972;5:269–74.
21. Reno VR, Nutini LG. Effect of magnetic fields on tissue respiration. Nature 1963;198:204–5.
22. Baranski S. Effect of chronic microwave irradiation on the blood forming system of guinea pigs and rabbits. Aerospace Med 1971;42:1196–9.
23. Luben RA, Cain CD, Chen MCY, et al. Effects of electromagnetic stimuli on bone and bone cells in vitro: inhibition of responses to parathyroid hormone by low-energy low-frequency fields. Proc Natl Acad Sci USA 1982;72:4180–4.
24. Wertheimer N, Leeper E. Electrical wiring configurations and childhood cancer. Am J Epidemiol 1979;109:273–84.
25. Wertheimer N, Leeper E. Adult cancer related to electrical wires near the home. Int J Epidemiol 1982;11:345–55.
26. Miller MW. Re: "Electrical wiring configurations and childhood cancer". (Letter.) Am J Epidemiol 1980;112:165–7.
27. Marshall E. Project ELF finally wins a vote. Science 1983;221:630–1.
28. Tomenius L. 50-HZ electromagnetic environment and the incidence of childhood tumors in Stockholm County. Bioelectromagnetics 1986;7:191–207.
29. Lin RS, Dischinger PC, Conde J, et al. Occupational exposure to electromagnetic fields and the occurrence of brain tumors. J Occup Med 1985;27:413–19.
30. Gilman PA, Ames RG, McCawley MA. Leukemia risk among U.S. white male coal miners—a case-control study. J Occup Med 1985;27:669–71.
31. Pearce NE, Sheppard RA, Howard JK, et al. Leukaemia in electrical workers in New Zealand. (Letter.) Lancet 1985;1:811–12.
32. Fulton JP, Cobb S, Preble L, et al. Electrical wiring configurations and childhood leukemia in Rhode Island. Am J Epidemiol 1980;111:292–6.
33. McDowall ME. Mortality of persons resident in the vicinity of electricity transmission facilities. Br J Cancer 1986;53:271–9.
34. Tornqvist S, Norell S, Ahlbom A, et al. Cancer in the electric power industry. Br J Ind Med 1986;43:212–13.
35. Vagero D, Olin R. Incidence of cancer in the electronics industry: using the new Swedish Can-

cer Environment Registry as a screening instrument. Br J Ind Med 1983;40:188–92.
36. McDowall ME. Leukaemia mortality in electrical workers in England and Wales. (Letter.) Lancet 1983;2:246.
37. Wright WE, Peters JM, Mack TM. Leukaemia in workers exposed to electrical and magnetic fields. (Letter.) Lancet 1982;2:1160–1.
38. Coleman M, Bell J, Skeet R. Leukaemia incidence in electrical workers. (Letter.) Lancet 1983;1:982–3.
39. Flodin U, Fredriksson M, Axelson O, et al. Background radiation, electrical work, and some other exposures associated with acute myeloid leukemia in a case-referent study. Arch Environ Health 1986;41:77–84.
40. Milham S. Mortality from leukemia in workers exposed to electrical and magnetic fields. (Letter.) N Engl J Med 1982;307:249.
41. Calle EE, Savitz DA. Leukemia in occupational groups with presumed exposure to electrical and magnetic fields. (Letter.) N Engl J Med 1986;313:1476–7.
42. Milham S. Mortality in workers exposed to electromagnetic fields. Environ Health Pers 1985;62:297–300.
43. Surveillance, Epidemiology, and End Results: incidence and mortality data 1973–77. In: Young JL, Percy CL, Asire AJ, eds. Natl Cancer Inst Monogr 1981:57.
44. World Health Organization. International classification of diseases for oncology. Geneva: World Health Organization, 1976.
45. Waksberg JE. Sampling methods for random digit dialing. J Am Stat Assoc 1978;73:40–6.
46. Kaune WT, Stevens RG, Callahan NJ, et al. Residential magnetic and electric fields. Bioelectromagnetics. 1987;8:315–35.
47. Prentice RL. Use of the logistic model in retrospective studies. Biometrics 1976;32:597–606.
48. Austin H, Cole P. Cigarette smoking and leukemia. J Chronic Dis 1986;39:417–21.
49. Severson RK. Cigarette smoking and leukemia. Cancer 1987;60:141–4.
50. Bross IDJ, Gibson R. Cats and childhood leukemia. J Med 1970;1:180–7.
51. Bross IDJ, Bentell R, Gibson R. Pets and adult leukemia. Am J Public Health 1972;62:1520–31.
52. Schneider R, Dorn CR, Klauber MR. Cancer in households: a human canine retrospective study. JNCI 1968;41:1285–92.
53. Hanes B, Gardner MB, Loosli CG, et al. Pet association with human cancers: a household questionnaire survey. JNCI 1970;45:1155–62.
54. Ishimaru T, Okada H, Tomiyasu T, et al. Occupational factors in the epidemiology of leukemia in Hiroshima and Nagasaki. Am J Epidemiol 1971;93:157–65.
55. Gardner MD. Current information on feline and canine cancers and relationship or lack of relationship to human cancer. JNCI 1971;46:281–90.
56. Easterly CE. Cancer link to magnetic field exposure: a hypothesis. Am J Epidemiol 1981;114:169–74.
57. Gordis L. Should dead cases be matched to dead controls? Am J Epidemiol 1982;115:1–5.
58. Polissar L, Severson RK, Boatman ES. A case-control study of asbestos in drinking water and cancer risk. Am J Epidemiol 1984;119:456–71.
59. Male JC, Norris WT, Watts MW. Exposure of people to power-frequency electric and magnetic fields. In: Anderson LE, Kelman BJ, Weigel RJ, eds. Interaction of biological systems with static and ELF electric and magnetic fields. Proceedings of the Twenty-third Annual Hanford Life Sciences Symposium. DOE Symposium Series 60, CONF-841041, 1987:407–18.