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Exposure to Magnetic Fields Among Electrical Workers in Relation to Leukemia Risk in Los Angeles County

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To address the hypotheses that electrical workers are exposed to higher magnetic fields and are at higher risk of leukemia than nonelectrical workers, we performed a registry-based case-control study among men aged 20–64 years with known occupation who were diagnosed with cancer in Los Angeles County between 1972 and 1990. Controls were men with cancers other than those of the central nervous system or leukemia. Magnetic field measurements on workers in each electrical occupation and in a random sample of occupations presumed to be nonelectrical were used to estimate magnetic field exposures for each occupation. Among men in electrical occupations, 121 leukemias were diagnosed. With the exception of electrical engineers, magnetic field exposures were higher among workers in electrical occupations than in nonelectrical occupations. A weakly positive trend in leukemia risk across average occupational magnetic field exposure was observed (odds ratio [OR] per 10 milligauss increase in average magnetic field = 1.2, 95% confidence interval [CI] 1.0–1.5). A slightly stronger association was observed for chronic myloid leukemia, although only 28 cases occurred among electrical workers (OR 10 milligauss increase = 1.6, 95% CI = 1.2–2.0). The results were not materially altered by adjustment for exposure to several agents known or suspected to cause leukemia. Although not conclusive, these results are consistent with findings from studies based on job title alone that electrical workers may be at slightly increased risk of leukemia.

Key words: electromagnetic fields, epidemiology, electrician, occupation, leukemia

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INTRODUCTION

In 1982, Milham reported elevated mortality from leukemia among men in 11 occupations with presumed exposure to electric and magnetic fields (electrical occupations). Subsequently, there have been numerous studies of leukemia mortality or incidence among workers in these occupations. Results are generally positive but not consistent with respect to the particular occupations at increased risk [Matanoski et al., 1993; Milham, 1985; Wright et al., 1982; Coleman et al., 1983; McDowall, 1983; Pearce et al., 1985, 1989; Calle and Savitz, 1985; Garland et al., 1990; Tynes et al., 1992; Preston-Martin and Peters, 1988; Tornqvist et al., 1986, 1991; Olin et al., 1985; Gilman et al., 1985; Flodin et al., 1986; Loomis and Savitz, 1990]. In only three studies of occupational exposure to magnetic fields in relation to leukemia risk was exposure assigned based on magnetic field measurements—a positive association was found in two [Floderus et al., 1993; Matanoski et al., 1993] but not in the other [Sahl et al., 1993].

The use of job title alone to assign exposure may introduce substantial misclassification. In addition, possible confounding of the association between work in electrical occupations and cancer risk by occupational exposures to other potential leukemogens has been investigated only in one study [Floderus et al., 1993].

We performed a registry-based case-control study of work in electrical occupations compared with nonelectrical occupations among men diagnosed with cancer in Los Angeles County. Measurements of occupational magnetic fields in workers in electrical occupations and a sample of nonelectrical occupations were used to assign exposure and examine exposure-response relationships. In addition, questionnaire assessment of occupational exposure to potential leukemogens was obtained to evaluate possible confounding by these other exposures.

METHODS

Subjects

This study included all males aged 20–64 years with a diagnosis of cancer reported to the comprehensive population-based cancer registry for Los Angeles County (The Cancer Surveillance Program) between 1972 and 1990 for whom an occupation at the time of diagnosis was recorded on the medical record. Cases were 2,355 men with the diagnosis of leukemia (ICD-0 morphology codes 980–994) [Percy et al., 1990]. Controls were 67,212 men diagnosed with other cancers. Persons with malignancies of the central nervous system (topography codes C70–C72) were excluded due to a proposed association with magnetic field exposure [Thomas et al., 1987].

Selection of Electrical Occupations for Measurement

To estimate exposure by electrical job category, we aimed to perform measurements on workers in as many of the 11 occupations originally listed by Milham [1982] as possible. Using the U.S. Bureau of the Census system of occupational classification [1970] (the system used by the Cancer Surveillance Program), we identified occupational categories equivalent to those of Milham. Three of the occupations listed by Milham (telegraph operators, aluminum workers, and streetcar and subway motormen) were not represented in Los Angeles during the period of study. Milham's

TABLE I. Number of Workers Monitored by Occupational Category

Occupational category	Number of workers
Electrical workers	278
Electrical engineers	14
Phone line workers and splicers	32
TV and radio repairmen	25
Electrical engineering technicians	13
Electrician and apprentices	33
Motion picture projectionists	15
Power station operators	37
Welders and flame cutters	22
Electric power wire and cable worker	87
Nonelectrical Workers	105
Accountants	6
Aeronautical and astronautical engineers	8
Carpenters	3
Construction laborers	3
Estimators and investigators	3
Foremen, not elsewhere classified	10
Janitors and sextons	9
Machine operatives	5
Machinists	5
Managers and administrators	5
Miscellaneous clerical workers	3
Miscellaneous mechanics and repairmen	3
Radiological technologists and technicians	8
Real estate agents and brokers	3
Stock clerks and storekeepers	8
Teachers—college and university	8
Teachers—other than college and university	8
Technicians, not elsewhere classified	7

original category of telephone and power linemen is divided into two categories in the U.S. Census Bureau system. The occupations we surveyed are listed in Table I.

Selection of Nonelectrical Occupations for Measurement

To characterize exposure among nonelectrical workers as a whole, we made magnetic field measurements on workers in a sample of nonelectrical jobs. We randomly selected 50 men from the subjects listed with the Cancer Surveillance Program who met the following criteria: white race, age 20–65 years, and diagnosed with cancer between 1972 and 1985. Using random numbers, the job titles of those subjects were ordered and the first 20 were selected for study. We made measurements on 18 of these occupations listed in Table I. Two categories randomly selected—sales representatives for manufacturing industries and farm laborers—were not measured for logistic reasons.

Assessment of Magnetic Field Exposure

To perform measurements, we sought companies that employed workers in the electrical and nonelectrical jobs of interest. We began with companies where we already had contacts. The category of college and university teachers was chosen randomly from the list of departments at the University of Southern California, for reasons of convenience. For occupations where we did not have contacts, we called companies listed in the phone book and asked to speak to the managers. When we obtained an interested employer with workers in the desired category we elicited their cooperation. A total of 15 companies participated in the Los Angeles area.

Once companies were selected, we asked personnel officers to identify all job titles within their companies that appeared on our list of potential titles within each occupational category that we wished to measure, or to identify those with comparable job duties.

We endeavored to characterize a typical workday for each occupation. Had we sampled a small number of days at random, we felt that we might not have captured a typical day's high exposure tasks that might have been performed more or less frequently on those days. Therefore, we constructed a typical workday by breaking down the day into component tasks which we expected would have relatively homogeneous exposures and then estimating the proportion of a typical workday spent in each task. Tasks were initially identified on the basis of a pilot study [Bowman et al., 1988] and refined by the industrial hygienist based on walk-through inspections that occasioned further measurements. In addition, the industrial hygienist interviewed a panel at each workplace that included one or more experienced workers, an experienced supervisor, the highest ranking member of the health and safety staff (if such a staff existed), and a representative of the management to determine how much time was spent in each task on average for each job. Where the same person fulfilled all roles, such as in a one-person radio and TV repair shop, one person was interviewed. Our industrial hygienist continued to probe the panel until a consensus was reached and the percent time in each task added up to 100%. To characterize historical exposures, the industrial hygienist also asked the panel about time spent in each task 15–20 years ago. Current measurements of magnetic fields were then applied to these historical time breakdowns to estimate past exposures.

Magnetic Field Measurements

Magnetic fields were measured using EMDEX monitors. Three EMDEX models were used during the course of the study—the prototype EMDEX and the EMDEX 100 (EPRI, Palo Alto, CA) and version C (EMF, Inc., W. Stockbridge, MA). All versions measure the magnetic fields in the 40–400 Hz frequency bandwidth which includes the frequency of the power supply in the United States (60 Hz). The monitors made measurements every 2.5 seconds. The EMDEX instruments were calibrated against the magnetic field from a standard coil with measured electrical current at the power frequency 60 Hz.

Workers wore these monitors for a work shift and kept a diary with start and stop times for each task. These data were supplemented by asking workers to press a button on the EMDEX at the beginning of each new task and having field staff observe the tasks done by the monitored workers and record start and stop times.

Assessment of Exposures to Other Potential Occupational Leukemogens

We assessed occupational exposure to agents that were either known or suspected leukemogens. The agents of a priori interest were ionizing radiation, benzene, chlorinated hydrocarbon solvents, other solvents, and pesticides. However, a complete listing of other exposures was also obtained. A structured questionnaire on occupational exposure in the present and 15–20 years ago was administered to the expert panel by the industrial hygienist. In particular, for each agent, the panel was asked about the percentage of employees exposed, the percent of time on the job exposed, and the intensity of exposure (low, medium, or high).

Statistical Methods

We created three indices of exposure for each occupational group—the mean, the time above 2.5 milligauss (mG), and the time above 25 mG. These exposure indices were expressed as a task-weighted estimate (TWE), constructed from a combination of the magnetic field measurements and the expert panel's assessment of the average time typically spent at these tasks over a year. We assigned the exposure estimates for a given occupational group to each individual within the occupational group.

The TWE for occupational category k is defined as:

$$TWE_k[X] = \sum_{c=company} \sum_{j=job} \frac{N_{cj}}{N_k} \sum_{i=task} p_{ijc} \sum_{m=worker} \frac{n_{im}}{n_i} \bar{X}_{im} \quad (1)$$

where c is a company, j is a job title in occupation k, i is a task, and m is a worker in occupation k monitored while performing task i. The weighting factor n_{im} is the number of measurements on worker m doing task i, n_i is the total number of measurements on task i, p_{ijc} is the proportion of time spent at task i with job j in company c (estimated by the expert panel), N_{cj} is the number of workers in job j at company C, and N_k is the number of workers in category k at all companies in study. $\bar{X}_{im}$ is the average exposure over time of worker m doing task i.

The standard deviation and variance for the TWEs are derived from a repeated measures random-effects analysis of variance (ANOVA) model. The exposure for each task is represented by:

$$X_{im}(t) = \mu_i + \mu_{im} + \epsilon_{im}(t) \quad (2)$$

where μ_i is a fixed task effect, μ_{im} a random effect due to task and worker, and $\epsilon_{im}(t)$ is a random effect due to task, worker, and time. The variables μ_{im} and $\epsilon_{im}(t)$ are normally distributed with means of zero and variances $\sigma^2_{\mu i}$ and $\sigma^2_{\epsilon i}$ which are conditional on the task i. The variance estimates $\hat{\sigma}^2_{\mu i}$ and $\hat{\sigma}^2_{\epsilon i}$ are derived by ANOVA, and substituted into eq. (1) to obtain the variances of the TWEs:

$$var[TWE_k[X]] = \sum_{c,i,j} \left(\frac{N_{cj}\, p_{ijc}}{N_k}\right)^2 \sum_{m} \left| \left(\frac{n_{im}}{n_i}\right)^2 \hat{\sigma}^2_{\mu i} + \sigma^2_{\epsilon i}/n_i \right| \quad (3)$$

We also calculated estimates of the geometric mean using a multiplicative model which corresponds to assuming a lognormal distribution of the data. However, because the additive model gives a direct estimate of the arithmetic mean which is the exposure measure of greatest interest, and because both models gave virtually identical ranking of occupations, we have chosen to focus on the results from the additive model.

We used the odds ratio (OR) to estimate associations between occupational category or magnetic field exposure estimates and leukemia risk. Age-adjusted OR and 95% confidence intervals (CI) were calculated using unconditional logistic regression [Breslow and Day, 1980]. To test for trend in leukemia risk with increasing magnetic field exposure, we assigned the mean task-weighted average exposure for that occupation to all subjects in that group and treated this variable as continuous in the logistic regression model. We present the tests for trend as the change in the OR per 10 mG increase in the current average magnetic fields or per 10 percentage point increase in the percent of time above either 2.5 or 25 mG. To calculate OR according to ordered categories of the three magnetic field exposure variables, we chose cut-points to provide adequate numbers in each category and maximal contrast between categories. We adjusted for age in 5-year categories.

To assess possible confounding by other occupational exposures, to each individual in an occupational group we assigned the probability of 1 for being exposed to the agent if exposure was reported for that occupation. For the nonelectrical workers, because we obtained information only on a random sample of 18 occupations, we used the proportion of the 18 occupations for which exposure was reported as the probability of ever being exposed to that agent for the entire group of nonelectrical workers. For example, if exposure to an agent was reported for only 1 of 18 nonelectrical occupations, each nonelectrical worker was given probability 1/18 of exposure to that agent.

For chlorinated hydrocarbon solvents, we also created variables for the percentage of employees exposed (three levels corresponding to none, 1–49%, 50+%) and the intensity of exposure (four levels corresponding to none, light, moderate, heavy). For nonelectrical jobs, the level of these variables was multiplied by the proportion of the 18 jobs with exposure to these agents to obtain a single value for all nonelectrical workers.

RESULTS

Magnetic field exposure estimates are shown by occupation in Table II. Magnetic field exposures for electrical workers were higher than those for nonelectrical workers for all four exposure indices ($p \leq 0.01$ for all comparisons). Among the electrical workers, only electrical engineers had lower exposures than nonelectrical workers. Task-weighted average mean exposure estimates of magnetic fields recently and 15–20 years in the past were quite similar. The ranking of electrical occupations varied according to the percentage of the workday that the exposure was above 2.5 mG as compared with 25 mG.

One hundred twenty-one cases of leukemia were diagnosed among workers in electrical occupations. The risk of leukemia for work in any of the electrical occupations was weakly elevated for all leukemias considered together (Table III) and did not vary materially by subtype.

ORs for leukemia by occupation are presented in Table IV. The numbers of subjects with leukemia within each occupational group are small. All of the OR are elevated, although statistically significantly so only for telephone linemen and splicers.

TABLE II. Current and Past Task-Weighted Average Workday Exposure to Magnetic Fields, Percentage of Time Above 2.5 and 25 mG Among Electrical and Nonelectrical Workers in Los Angeles County, 1972–1990

Occupation	Current average magnetic field (mG)	Average magnetic field 15–20 years ago (mG)	Percent of workday with magnetic field >2.5 mG	Percent of workday with magnetic field >25 mG
Electrical workers				
Electrical engineer	1.6 (0.1)[a]	1.6 (0.1)	11.7 (1.3)	0.3 (0.1)
Phone line worker and splicer	2.7 (0.4)	2.7 (0.3)	25.7 (4.2)	0.5 (0.2)
TV and radio repairman	3.4 (0.4)	3.4 (0.4)	46.9 (7.2)	0.3 (0.1)
Electrical engineering technician	3.4 (0.3)	2.9 (0.2)	28.8 (2.5)	1.5 (0.4)
Electrician and apprentice	7.0 (1.7)	5.8 (1.3)	33.6 (2.6)	6.2 (2.2)
Motion picture projectionist	8.0 (1.9)	8.9 (2.2)	55.8 (8.3)	7.8 (5.1)
Power station operator	17.1 (7.7)	16.3 (7.2)	40.0 (2.5)	12.4 (2.4)
Welder and flame cutter	19.5 (6.9)	20.1 (7.3)	32.2 (2.7)	8.0 (1.3)
Electric power wire and cable worker	23.6 (4.1)	23.4 (3.7)	35.5 (1.8)	11.3 (1.3)
All electrical workers	9.6 (1.3)	9.5 (1.2)	34.5 (1.7)	5.4 (0.7)
Nonelectrical worker	1.7 (0.1)	1.8 (0.1)	12.9 (1.3)	0.4 (0.5)

[a]Mean, and in parentheses, standard deviation.

TABLE III. Age-Adjusted OR for Employment at Time of Diagnosis in Electrical Occupations According to Leukemia Subtype, 1972–1990*

Leukemia type	Cases in electrical occupations	Cases in nonelectrical occupations	OR[a]	95% CI
All leukemias	121[b]	2,234	1.3	1.1–1.6
Acute nonlymphocytic leukemia	41	812	1.2	1.0–1.6
Chronic lymphocytic leukemia	28	506	1.3	1.0–1.8
Chronic myloid leukemia	25	462	1.3	0.8–2.1

*OR, odds ratio; CI, confidence interval.
[a]Relative to nonelectrical occupations. Controls for all comparisons are employed males aged 20–64, with cancer other than leukemia or central nervous system cancer. Of these, 2,665 were employed in electrical occupations, 64,547 were not.
[b]Includes leukemias not classifiable into the other three categories.

We observed a modest increase in the risk of leukemia across the three categories of the average magnetic field and percent of time above 25 mG although point estimates were of only borderline statistical significance (Table V). When we treated these exposures as continuous variables, we observed a stronger trend for the percent of time above 25 mG than for current average magnetic field exposure although the estimates are somewhat unstable.

We did not observe a clear association between our indices of magnetic field exposure and either acute nonlymphocytic leukemia (Table VI) or chronic lymphocytic leukemia (Table VII). Although numbers of exposed subjects with chronic myloid leukemia were small, the highest category of both current average magnetic field exposure and percent of time above 25 mG was associated with a 2.3-fold increased risk (Table VII).

We considered the possibility that the choice of an additive model for computing task-weighted average exposure rather than a multiplicative model (consistent with a

TABLE IV. Age-adjusted OR for Leukemia by Category of Electrical Occupation Among Men Aged 20–64 Years and Diagnosed With Cancer in Los Angeles County, 1972–1990*

Occupational category	Leukemias	Controls	OR	95% CI
Electrical engineer	30	613	1.4	1.0–1.9
Phone line worker and splicer	4	31	3.2	1.5–7.0
TV and radio repairman	4	106	1.2	0.5–2.9
Electrical engineering technician	24	521	1.2	0.9–1.7
Electrician and apprentice	28	728	1.2	0.8–1.6
Motion picture projectionist	1	22	1.3	0.3–6.4
Power station operator	1	15	1.7	0.4–7.6
Welder and flame cutter	27	579	1.4	0.9–2.3
Electric power wire and cable worker	2	50	1.2	0.4–3.8
Nonelectrical worker	2,234	64,547	1.0	—[a]

*OR, odds ratio; CI, confidence interval.
[a]Reference category.

TABLE V. OR for Leukemia According to Estimates of Average Magnetic Field and Percent of Workday Above 2.5 and 25 mG by Occupation

Variable and category	Cases	Controls	OR (95% CI) categorical[a]	OR (95% CI) per 10 unit increase (continuous)
Average magnetic field mG				
<1.7	2,264	65,160	1.0	
1.8–8.0	61	1,408	1.2 (1.0–1.6)	
8.1	30	644	1.4 (1.0–2.0)	
All	2,355	67,212		1.2 (1.0–1.5)
Percent of time>2.5 mG				
>13.0	2,264	65,160	1.0	
13.0–32.9	55	1,131	1.4 (1.1–1.8)	
33.0[a]	36	921	1.2 (0.9–1.6)	
All	2,355	67,212		1.1 (1.0–1.2)
Percent of time>25 mG				
<0.5	2,268	65,266	1.0	
0.5–7.9	57	1,302	1.2 (1.0–1.6)	
>7.9	30	644	1.4 (1.0–2.0)	
All	2,355	67,212		1.4 (1.0–2.1)

[a]OR (odds ratio) are age adjusted. CI, confidence interval.

lognormal distribution of the data) influenced our results. The dose-response relation for the multiplicative model was more strongly positive, consistent with the more truncated distribution of geometric means, but with wider CI than results from the additive model (data not shown).

Our questionnaire regarding exposure to several agents known or suspected to cause leukemia revealed that workers in some of the electrical occupations were exposed to ionizing radiation, gasoline exhaust (a possible surrogate for benzene exposure), chlorinated hydrocarbon solvents, and other solvents (Table VIII). Among the 18 nonelectrical occupations surveyed, exposure to ionizing radiation and benzene was reported for one occupation, exposure to gasoline exhaust for one occupation, exposure to chlorinated hydrocarbon solvents for three occupations (one of these was also exposed to ionizing radiation and benzene), and exposure to other solvents was

TABLE VI. ORs for Acute Nonlymphocytic Leukemia According to Estimates of Average Magnetic Field Exposure and Percent of Time Exposed Above 2.5 and 25 mG by Occupation

Variable and category	Cases[a]	OR (95% CI) categorical[b]	OR (95% CI) per 10 unit increase (continuous)
Average magnetic field (mG)			
<1.7	820	1.0	
1.8–8.0	23	1.3 (0.9–1.9)	
8.1[b]	10	1.3 (0.7–2.3)	
All	853		1.2 (0.8–1.6)
Percent of time >2.5 mG			
<13.0	820	1.0	
13.0–32.9	21	1.5 (1.0–2.2)	
33.0[b]	12	1.1 (0.6–1.9)	
All	853		1.1 (0.9–1.3)
Percent of time >25 mG			
<0.5	820	1.0	
0.5–7.9	23	1.4 (0.9–2.0)	
>7.9	10	1.3 (0.7–2.3)	
All	853		1.4 (0.8–2.6)

[a]Numbers of controls are the same for analyses of all types of leukemia. See Table V.
[b]ORs (odds ratio) are age adjusted. CI, confidence interval.

reported for four occupations. Exposure to herbicides, of interest because of their use in clearing power and telephone line rights-of-way, was not reported for any of the occupations. Although ever being exposed to solvents was more common among electrical workers, there was no striking excess of exposure to other potential leukemogens among electrical workers. The pattern of exposures estimated for the 15–20 years in the past was very similar (data not shown).

We examined the frequency and intensity of exposure to chlorinated hydrocarbon solvents because several occupational groups were exposed to these agents. Of the electrical occupations with reported exposure to these agents, the percentage of workers repeated to be exposed was 100% in the categories of electricians and apprentices, power station operators, and TV and radio repairmen, 50% of the phone line workers and splicers, and 25% of the electrical power line and cable workers and electrical engineering technicians. Among the three nonelectrical occupations with reported exposure to chlorinated hydrocarbon solvents, two were reported to be exposed 100% of the time and one was reported to be exposed less than 25% of the time. High intensity exposure was reported only for electrical power line and cable workers. These variables were not positively associated with leukemia risk in these data and did not confound the association between magnetic field exposure and leukemia risk.

DISCUSSION

Our results confirm that exposure to magnetic fields among workers in electrical occupations is higher than among workers in nonelectrical occupations. Workers in electrical occupations were at slightly higher risk of leukemia than workers in nonelectrical occupations. A weak positive trend of only borderline statistical significance, was observed between occupation-specific magnetic field measurements and

TABLE VII. ORs for Chronic Lymphocytic Leukemia and Chronic Myeloid Leukemia According to Estimates of Average Magnetic Field Exposure and Percent of Workday Above 2.5 and 25 mG by Occupation

Variable and category	Cases	OR (95% CI) categorical[a]	OR (95% CI) per 10 unit increase (continuous)
Chronic lymphocytic leukemia			
Average magnetic field (mG)			
<1.7	512	1.0	
1.8–8.0	18	1.6 (1.2–2.3)	
8.1[a]	4	0.8 (0.4–1.5)	
All	534		1.0 (0.6–1.5)
Percent of time >2.5 mG			
<13.0	512	1.0	
13.0–32.9	12	1.4 (0.9–2.1)	
33.0[a]	10	1.4 (0.8–2.2)	
All	534		1.1 (1.0–1.3)
Percent of time >25 mG			
<0.5	514	1.0	
0.5–7.9	16	1.6 (1.1–2.3)	
>7.9	4	0.8 (0.4–1.6)	
All	534		1.0 (0.5–2.2)
Chronic myeloid leukemia			
Average magnetic field (mG)			
<1.7	469	1.0	
1.8–8.0	8	0.8 (0.5–1.3)	
8.1[a]	10	2.3 (1.4–3.8)	
All	487		1.6 (1.2–2.0)
Percent of time >2.5 mG			
<13.0	469	1.0	
13.0–32.9	11	1.3 (0.8–2.3)	
33.0[a]	7	1.1 (0.6–2.2)	
All	487		1.1 (0.9–1.4)
Percent of time >25 mG			
<0.5	469	1.0	
0.5–7.9	8	0.8 (0.5–1.4)	
>7.9	10	2.3 (1.4–3.8)	
All	487		2.2 (1.3–3.7)

[a]ORs (odds ratio) are age adjusted. CI, confidence interval.

risk of all leukemias. Chronic myloid leukemia was more strongly associated with magnetic field measurements but numbers in this subgroup were small. The relationships were not appreciably altered by adjustment for exposure to several substances known or suspected to be involved in the etiology of leukemia.

We previously reported analyses of mean magnetic field exposure in relation to risk of all leukemias combined and acute nonlymphocytic leukemia [Bowman et al., 1992]. A 4 level categorization was used in that report in which the reference category was limited to nonelectrical workers although electricians had lower mean exposure. In the current analysis we created categories based entirely on the occupation-specific magnetic field exposure estimates rather than using nonelectrical workers as an arbitrary reference group. Further, because we included analyses by 3 subtypes of leukemia in the current analysis, we used three rather than four levels to maintain the

TABLE VIII. Current Exposure (Ever vs. Never) to Agents Known or Suspected to Cause Leukemia as Assessed by Questionnaire According to Electrical Occupational Category, Los Angeles County, 1972–1990

	Agent				
Occupational category	Ionizing radiation	Benzene	Gasoline exhaust	Chlorinated hydrocarbon solvents	Other solvents
Electrical engineer	–[a]	–	–	–	–
Phone line worker and splicer	–	–	–	+	+
TV and radio repairman	–	–	–	+	+
Electrical engineering technician	–	–	+	+	+
Electrician and apprentice	+	–	–	+	+
Motion picture projectionist	–	–	–	–	–
Power station operator	–	–	–	+	+
Welder and flame cutter	–	–	–	–	–
Electric power wire and cable worker	–	–	+	+	+

[a]– indicates never exposed, + indicates exposed at least part of the time.

same categories for all tables. As a result, the results differ slightly from the previous analysis in which no suggestion of a trend across the four categories was observed.

In only two other studies has the possible association between work in electrical occupations and leukemia risk been estimated using measurements of magnetic fields on the job rather than job title [Sahl et al., 1993; Matanoski et al., 1993]. No appreciable association between magnetic field measurements and leukemia risk was reported in the study of Sahl et al. [1993]—an association between the fraction of measurements above 50 mG and leukemia risk was attributed to an outlier. However in that study, the number of leukemias was small—41, including only 17 among electrical workers. Among telephone company workers, Matanoski et al. [1993] observed an approximate 2-fold increase in risk for workers in the upper 50th percentile of measured occupation-specific mean and peak exposures. Floderus et al. [1993] studied all employed workers in two Swedish counties, rather than focusing on workers in electrical occupations and observed an association between measured magnetic fields and the risk of leukemia, particularly chronic lymphocytic leukemia. The trend was stronger than that observed in our data, possibly reflecting more extensive exposure measurements in that study.

Our study has several limitations. Magnetic field measurements that we considered to be representative for each electrical occupation were assigned to individuals. This is the same approach used in the studies of Sahl et al. [1993], Floderus et al. [1993], and Matanoski et al. [1993]. Assigning a group mean to individuals results in measurement error of the Berkson type that does not attenuate the dose response but inflates the standard error and therefore decreases the power of the study [Armstrong, 1990]. Comparisons between our study and others suggest that magnetic field exposures for a given occupational category differ markedly across workplaces and industries [Sahl et al., 1993; Matanoski et al., 1993; Tornqvist et al., 1991] as well as within a given workplace [Tornqvist et al., 1991]. In our study as well as those of Sahl et al. [1993] and Matanoski et al. [1993], measurements for a given occupation were generally made only at one worksite. As a result, the precision of the exposure estimates will be limited resulting in the "classical" type of misclassification and attenuation of the dose-response relationship. Our exposure assessment is also limited because we had information only on occupation at the time of diagnosis. Although most of the electrical job categories require substantial training, it is possible that some persons we classified as nonelectrical workers had previously worked in electrical occupations. Further, we do not know how long subjects had worked in their occupations. Thus, some electrical workers may only have been in these occupations for a short period of time. Both of these limitations should lead to nondifferential misclassification and a bias toward the null.

The only other study to assess exposure to other potential leukemogenic agents was that of Floderus et al. [1993]. No evidence of confounding was observed in either study. Neither study included direct measurements of exposure to other agents. The reliance on questionnaire assessment is likely to have introduced misclassification in the specification of these other exposures. These exposures were probably classified with more precision in the study by Floderus et al. [1993] because a large number of workplaces were surveyed. Although incomplete control of confounding may have occurred in both studies, there was no clear evidence that workers in jobs with higher exposures to magnetic fields were more likely to be exposed to potential leukemogens than workers in jobs with lower magnetic field exposures. Furthermore, in our study, these other exposures were not positively associated with leukemia risk.

Another limitation of our study is that our controls were subjects with cancers other than leukemia and malignancies of the central nervous system and may not have been representative of the population that gave rise to the cases. It is possible that other cancers may be related to magnetic field exposure and thus our data would be biased toward the null. In addition, the proportion of smokers will be higher among persons diagnosed with cancers other than leukemia and brain tumors before the age of 65 years than in the general population. To the extent that smoking is jointly associated with the risk of leukemia and the probability of working in an electrical occupation, our study may have been biased in either direction. However, because smoking is only weakly associated with leukemia risk [Brownson et al., 1993], it is unlikely to confound our results. Further, our results are based on the proportion of leukemia among all cancers rather than the absolute incidence of leukemia. If workers in electrical occupations have a lower incidence of other cancers than nonelectrical workers, the OR for leukemia could be spuriously elevated relative to nonelectrical workers. However, in order for this potential bias to explain our results, it would have had to produce an inverse trend with magnetic field measurements, which seems unlikely. In addition, this type of bias would operate equally across types of leukemia and not produce the stronger association with chronic myloid leukemia observed in our data.

Our results confirm that workers in electrical occupations experience higher exposures to magnetic fields than workers in nonelectrical occupations. The weak positive trend that we observed between measured fields and risk of all leukemias combined and, in particular, chronic myloid leukemia might reflect the truth, attenuation by several sources of misclassification of a stronger association, or the play of chance.

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