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Leukemia following Occupational Exposure to 60-Hz Electric and Magnetic Fields among Ontario Electric Utility Workers

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In a nested case-control study of 1,484 cancer cases and 2,179 matched controls from a cohort of 31,543 Ontario Hydro male employees, the authors evaluated associations of cancer risk with electric field exposure and reevaluated the previously reported findings for magnetic fields. Pensioners were followed from January 1, 1970, and active workers (including those who left the corporation) from January 1, 1973, with both groups followed through December 31, 1988. Exposures to electric and magnetic fields and to potential occupational confounders were estimated through job exposure matrices. Odds ratios were elevated for hematopoietic malignancies with cumulative electric field exposure. After adjustment, the odds ratio for leukemia in the upper tertile was 4.45 (95% confidence interval (CI) 1.01–19.7). Odds ratios were also elevated for acute nonlymphoid leukemia, acute myeloid leukemia, and chronic lymphoid leukemia. For cumulative magnetic field exposure, there were similar elevations that fell with adjustment. Evaluation of the combined effect of electric and magnetic fields for leukemia showed significant elevations of risk for high exposure to both, with a dose-response relation for increasing exposure to electric fields and an inconsistent effect for magnetic fields. There was some evidence of a nonsignificant association for brain cancer and benign brain tumors with magnetic fields. For lung cancer, the odds ratio for high exposure to electric and magnetic fields was 1.84 (95% CI 0.69–4.94). *Am J Epidemiol* 1996;144:150–60.

electromagnetic fields; leukemia; neoplasms; occupational diseases

In 1979 it was first suggested that residential exposure to electric and magnetic fields might lead to increased cancer risk in children (1). Since then a number of studies have examined the possible relations between exposure to a range of electric and magnetic field sources and cancer. High voltage transmission lines and distribution network lines are among the field sources considered in these studies. An inconsistent increase in the risk of cancer was observed among both the general population exposed (1–7) and the workers where high exposure to electric and/or magnetic fields seemed likely (8–24).

Our findings for occupational exposure to magnetic fields derived from power frequencies of 50–60 Hz arising from employment in Electricité de France, Hydro Québec, and Ontario Hydro have been reported previously (25). As the excess of leukemia in this triutility study came primarily from the Ontario Hydro component, further analyses were performed incorporating more detailed data on potential occupational confounders (principally exposure to leukemogens), data on additional workers evaluated for exposure to electric and magnetic fields, and some additional cases of leukemia ascertained as eligible after the data set had been finalized for the triutility analysis. The present report gives the findings from these analyses, with particular attention to electric field exposure, as well as a reevaluation of the effects of magnetic field exposure.

MATERIALS AND METHODS

This was a nested case-control study within a study base of active male employees of Ontario Hydro from January 1, 1973, on, together with those pensioners known to be alive on January 1, 1970. New male employees who entered the work force and those who became pensioners from January 1, 1973, to December 31, 1988, were included in the study base. The period of observation for the detection of cases of cancer began after 1 year of full employment and ceased with the death of the worker or on December 31, 1988, whichever was earlier.

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Abbreviation: CI, confidence interval; ICD, *International Classification of Diseases*.

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Cancer cases were ascertained through record linkage of the total study cohort with the records of the Ontario Cancer Registry. With records dating from 1964, the Ontario Cancer Registry covers the whole province of Ontario and is among the most complete in Canada. Cases were defined as those cancers within *International Classification of Diseases* (ICD) codes 140–208, and including code 225, newly diagnosed in the relevant time period among male employees with at least 1 year of continuous service. The relevant time period for linkage was 1970–1988 for the retirees and 1973–1988 for the active workers. Only the first primary tumor in an individual was eligible; previous or new basal or squamous cancers of the skin were disregarded (they are not registered by the Ontario Cancer Registry).

In the triutility study (25), it was decided that malignant melanoma of the skin and choroid (ICD codes 172 and 190.6), all malignant and benign brain tumors (ICD codes 191 and 225), and all hematologic malignancies (ICD codes 200–208) were of a priori interest for risk from exposure to magnetic fields, and they were regarded as "a priori cancers" for the present analysis.

Selection of controls was made from the files of Ontario Hydro according to an equal probability (random) selection among all employees. The matching criteria used were the same year of birth, being alive in the year of diagnosis of the case, and having no evidence of prior diagnosis of any cancer (including ICD code 225) except basal or squamous cancer of the skin. The aim was to select four controls for cancers defined as of a priori interest and one control for each other cancer.

Information on both cases and controls was obtained from the relevant sources in Ontario Hydro files. Personal identifying information was used to ensure reliable identification and included the full name and date of birth. An attempt was also made to collect the Ontario Health Insurance Number from the company medical files to facilitate the resolution of uncertain linkages with the Ontario Cancer Registry. A complete occupational history up to the date of diagnosis of the (relevant) case was also obtained. These data included a complete record of all occupations within Ontario Hydro until the date the individual left or retired from the company. The occupational histories were coded by job title and job site. Those who retired prior to the date of the diagnosis of the case were presumed to have had no subsequent relevant occupational exposure. Those who left the company prior to the date of the diagnosis of the case and prior to the normal retirement date would have had an opportunity for relevant occupational exposure, but no details of such exposure were available.

Evaluation of exposure to electric and magnetic fields

Each study subject was assigned an exposure to electric and magnetic fields using a job exposure matrix that took into account the job title, work location, and calendar time. The job exposure matrix was created from direct measurements of worker exposure under usual working conditions using the Positron model 378108 personal exposure monitor (Positron Industries, Montreal, Quebec, Canada). As measurements could not be made on the actual study subjects, 895 workers in the current work force were selected for monitoring according to job title for 5 working days. A listing of job titles held by the cases and controls in the study was prepared from the work histories. The list, with no identification of case and control status, was structured in terms of the frequency of job titles and used as the basis for selection of workers to be monitored. The number of workers with a specific job title selected for monitoring was proportional to the frequency with which it appeared in the list of job titles. It became apparent during this process that the site of work was an important parameter influencing the level of exposure, so whenever possible measurements were made at the same sites or similar sites as described in the job histories. In total, 260 unique job titles at 140 different work sites were sampled.

Because the number of job titles for all study subjects exceeded the number that could feasibly be measured, job titles were subsequently grouped into job categories. The job categories for the job exposure matrix were derived by first preparing an occupational profile of each of the 260 monitored job titles. Each job was reviewed against a set of 29 factors describing the type of activities (e.g., professional, managerial, clerical, trades, work with electric system or not) and work environments (e.g., time spent near high voltage/high current equipment, seasonal variations, work inside or outside, work within a specific location, travel to different locations) that applied to the job. This process reduced the original 260 job titles to 110 groups with identical occupational profiles. The 110 groups were then analyzed and combined into final job exposure matrix categories, based on the distribution of arithmetic and geometric means for electric and magnetic field exposures, on the profiles, and on consideration of past changes in these factors. This resulted in 17 job categories in the job exposure matrix. An examination of job category with regard to work location revealed that the type of work location for 11 job categories could be used to provide estimates of exposure stratified by work location.

Once the job categories were established, arithmetic and geometric means of electric and magnetic field exposures were calculated from the daily work periods of sampled workers and entered into the job exposure matrix. The jobs held by study subjects were individually coded as to their appropriate job category using the above-mentioned occupational profiles developed in consultation with staff knowledgeable about jobs and work practices.

To determine the extent to which historical exposures in relevant jobs had changed, the historical records of the company (and relevant current and retired supervisory personnel) were consulted. This process had to be extended back in time to the date of hire of the oldest cases and controls. This included the period 1949–1959 when the 25-Hz and 66⅔-Hz components of the electric transmission and distribution systems were converted to 60 Hz. Past exposures to electric and magnetic fields were judged to have differed from present if changes had occurred in exposure sources, work sites, or work procedures. Adjustments for sources were judged to be the major factor and were derived for the years back to 1950 for five types of site or facility. The source adjustment factors were based on a combination of data available from Ontario Hydro archives. These included peak power loads at a number of specific points in the Ontario Hydro system and overall system data, such as the total energy generated, operating voltages, and total lengths of transmission and distribution circuits. These were used to estimate average voltages and currents in different parts of the system through the period 1950–1990. Prior to 1950 no further adjustments were made because of increasing difficulties in locating specific load data and an increasing uncertainty in the assumptions of the source models.

To convert these data into estimates of individual exposure for each study subject, we applied the exposure estimates of the appropriate cells in the job exposure matrix for the relevant job titles and work locations in the individuals' work history to the days worked, which were then summed to produce a cumulative life exposure index. These indices are available in terms of cumulative arithmetic and cumulative geometric means for both electric and magnetic field exposure estimates.

Potential occupational confounders

The basic data on potential occupational confounders were developed by an industrial hygienist at Ontario Hydro from a job title list developed before the establishment of the electric and magnetic fields' job exposure matrix, based on all known exposure to carcinogens classified by the International Agency for Research on Cancer as in categories 1, 2A, and 2B. For ionizing radiation, quantitative estimates of occupational exposure were available from the Ontario Hydro Radiation Dose Information System, which is maintained in accordance with the Atomic Energy Control Act.

Because the triutility analysis showed that special attention needed to be paid to exposure to leukemogens (25), a secondary list of job titles and work sites related only to the cases of leukemia and corresponding controls was developed. This list, blind as to case and control status, was submitted to an occupational medicine specialist, knowledgeable in terms of potentially hazardous exposures of the work place. Job titles with "possible" or "probable" exposure to carcinogens were first identified. These job titles were then recombined into individual work histories (still blind as to case or control status), and the sets were reclassified, identifying those for whom exposure to potential leukemogens was possible or probable. Following this classification process, the lists were examined by an occupational hygienist independent of Ontario Hydro, and consultations were held with occupational hygienists in Ontario Hydro.

Analysis

The study was initially analyzed in the univariate mode, providing unadjusted estimates of odds ratios with the estimated cumulative exposure to electric and magnetic fields being the primary exposures of interest. Exposures to electric and magnetic fields were measured as continuous variables. In the subsequent logistic regression analysis, these measurements were categorized into tertiles, based on the distribution of exposures in the controls, to estimate odds ratios and their corresponding 95 percent confidence intervals for each of the higher levels of exposure in comparison with the lower reference level. All dose-response relations were tested by the χ^2 test for trend, and the statistical significance was determined by the p value calculated accordingly.

The effect of potential confounding variables was evaluated using conditional logistic regression techniques appropriate to matched studies. Socioeconomic status was classified by a five-category scheme felt to represent the employee status at the time of hire. Potential confounders were categorized or considered as continuous variables as appropriate to the data collected. For example, three levels of exposure to ionizing radiation were defined, with 0 = no exposure (used as the reference comparison), 1 = less than 5 rems, and 2 = 5 or more rems of exposure.

The potential occupational confounders for which adjustment was made in the analysis varied by cancer site in the light of published information on risk. For leukemia, the potential occupational confounders for which adjustment was made were ionizing radiation, (2,4-dichlorophenoxy)acetic acid (2,4-D), (2,4,5-trichlorophenoxy)acetic acid (2,4,5-T), and benzene. For non-Hodgkin's lymphoma, adjustment was for (2,4-dichlorophenoxy)acetic acid and (2,4,5-trichlorophenoxy)acetic acid exposure. For brain cancer, adjustment was for ionizing radiation; for melanoma, sunlight; and for lung cancer, ionizing radiation, asbestos, cadmium, and cadmium compounds.

Evaluation of the combined effects of electric and magnetic fields was made by analyzing the fields as continuous variables and by categorizing the exposures simultaneously into a 3 × 3 matrix, with the boundaries of the tertiles of exposures the same as when the exposures were considered alone. As terms for interaction between electric and magnetic fields were significant for the risk of leukemia, these terms were included in the final model.

RESULTS

There were 1,484 eligible cancer cases for the study. Of these, 233 were "a priori cancers" and 1,251 were cancers of other sites. Of the a priori cancers, 230 were matched to four controls, two to three controls, and one to two controls. The remainder were matched to one control, resulting in a total of 2,179 controls and a total study population of 3,663 subjects.

Pensioners comprised 46.2 percent of the 3,663 subjects; 40.6 percent of the population were still actively working at the utility at the time of diagnosis, the remainder having left before becoming pensioners. At the end of the period of observation (December 31, 1988), 57.4 percent of the cases were known to be deceased. Of the 221 cases among workers who had left the utility, 55.7 percent were deceased. More than half of the study subjects were born before 1920. The majority of the cancers (66.4 percent) were diagnosed after 1980. The average ages when first employed at Ontario Hydro were 31.8 years for both the cases and controls. Less than 10 percent of the study population started working at the utility prior to 1930, and the majority were hired after 1945, which coincided with a period of provincewide recruitment and enhanced electricity generation. Fifty percent of the cases and 54 percent of the controls ceased working for the utility in 1980 or more recently. Only about 13 percent had less than 10 years of employment at the utility. Sixty-nine percent of the cases and 64 percent of the controls had at least 20 years of employment at the utility.

Table 1 shows the frequency distributions of cumulative arithmetic (for simplicity referred to subsequently as "cumulative") field measurements for all cases and controls. The median and mean exposures of cases and controls to both electric and magnetic fields were similar.

TABLE 1. Distribution of cumulative exposures to electric and magnetic fields among Ontario electric utility workers, 1970–1988

Levels	Cases		Controls	
	No.	%	No.	%
Cumulative electric (V/m-years)				
0–4.9	0	0.0	0	0.0
5–9.9	1	0.1	4	0.2
10–24.9	22	1.5	45	2.1
25–49.9	43	2.9	116	5.3
50–99.9	127	8.6	236	10.8
100–249	476	32.1	692	31.7
250–499	470	31.7	638	29.3
500–999	197	13.3	218	10.0
1,000–2,499	147	9.9	227	10.4
2,500–4,999	1	0.1	3	0.1
≥5,000	0	0.0	0	0.0
Total	1,484		2,179	
Cumulative magnetic (μT-years)				
0–0.09	0	0.0	0	0.0
0.1–0.24	4	0.3	5	0.2
0.25–0.49	13	0.9	31	1.4
0.5–0.99	46	3.1	87	4.0
1.0–2.4	260	17.5	410	18.8
2.5–4.9	383	25.8	591	27.1
5.0–9.9	415	28.0	588	27.0
10–24.9	195	13.1	250	11.5
25–49.9	67	4.5	91	4.2
50–99.9	55	3.7	67	3.1
100–249.9	45	3.0	58	2.7
≥250	1	0.1	1	0.0
Total	1,484		2,179	

Of the 233 cancers in sites of a priori interest, 140 were hematopoietic malignancies, 35 were brain tumors (including both malignant and benign), and 58 were malignant melanoma of the skin (table 2). Of the 140 hematopoietic malignancies, 50 were leukemias. The largest numbers of the other cancer sites were lung (n = 263) and prostate (n = 244). Of the 50 cases of leukemia, 13 were acute myeloid leukemia (ICD codes 205.0 and 205.9), eight were chronic myeloid leukemia, 19 were chronic lymphoid leukemia (ICD code 204.1), and 10 were "unspecified" leukemia. The category acute nonlymphoid leukemia is a combination of ICD codes 205.0, 205.3, 205.9, 206.0, 207.0, 207.2, 207.8, 208.0, and 208.9 and includes the 13 acute myeloid leukemia cases and seven of the unspecified.

Odds ratios for cancer sites and cumulative exposures to electric fields are presented in table 3. Unad-

TABLE 2. Cancers ascertained according to site among Ontario electric utility workers, 1970–1988

	No.	%
Sites of a priori interest		
All hematopoietic malignancies	140	9.4
Non-Hodgkin's lymphoma	51	3.4
All leukemia	50	3.4
Chronic lymphoid leukemia	19	
Acute myeloid leukemia	13	
Chronic myeloid leukemia	8	
Other and unspecified leukemia	10	
Other hematopoietic and lymphatic malignancies	39	2.6
All brain	35	2.4
Malignant brain tumors	24	
Benign brain tumors	11	
Malignant melanoma of the skin	58	3.9
Other sites		
Lips, buccal, and pharynx	67	4.5
Stomach	44	3.0
Colon	168	11.3
Rectum	76	5.1
Other gastrointestinal tract	80	5.4
Lung	263	17.7
Other respiratory	30	2.0
Other bone and connective tissues	20	1.4
Prostate	244	16.4
Other male genital organs	25	1.7
Urinary	160	10.8
Other solid tumors	74	5.0
Total	1,484	

justed odds ratios are presented along with odds ratios adjusted for socioeconomic status, year started at Ontario Hydro, and potential occupational confounders where applicable.

Of the sites of a priori interest, elevated odds ratios were noted for all except malignant and benign brain tumors. After adjustment, the odds ratios increased for all leukemia and the subtypes, the odds ratio for the upper tertile for all leukemia being 4.45 (95 percent confidence interval (CI) 1.01–19.7). There was a suggestion of a dose-response relation for each of these sites, but the test for trend was not significant for any of them after adjustment. For the other sites, although odds ratios were elevated for stomach and lung cancer, none were significantly elevated after adjustment.

Odds ratios for cancer sites and cumulative exposures to magnetic fields are presented in table 4. Odds ratios were elevated for all leukemia, acute nonlymphocytic leukemia, and acute myeloid leukemia, but they fell after adjustment. For both malignant and benign brain tumors, odds ratios were elevated, especially after adjustment for potential occupational confounders, but the associations were not statistically significant.

The distributions of the numbers of cases of leukemia and their controls for exposure to electric and magnetic fields, along with the odds ratios derived from these distributions for the joint effects of cumulative electric and magnetic field exposure, are shown in table 5. The numbers in some of the cells are sparse, but 17 (34 percent) of the cases had high exposure to both electric and magnetic fields compared with 34 (17 percent) of the controls. Also in the table are odds ratios presented for an additive model with no terms for interaction between electric and magnetic fields. Within each level of magnetic field exposure, there is increasing risk with increasing exposure to electric fields, but none of the odds ratios are significantly elevated. Within each level of electric field exposure, there is no indication of increasing risk with increasing exposure to magnetic fields. There was a similar finding (not tabulated here) when exposure was treated as continuous variables, though it was necessary because of skewness of the distributions to substitute the values outside the interquartile range by the corresponding quartile value. The odds ratios were 4.27 (95 percent CI 1.00–18.17) for high exposure to electric fields and low exposure to magnetic fields, 4.79 (95 percent CI 1.03–22.22) for high exposure to electric fields and medium exposure to magnetic fields, and 5.53 (95 percent CI 0.88–34.63) for high exposure to both electric and magnetic fields.

In addition, in table 5, the odds ratios are presented for a model with electric and magnetic field exposures categorized and with terms for interaction between electric and magnetic fields. For each level of exposure to magnetic fields, there is an increase in the risk of leukemia for increasing exposure to electric fields, with the exception of no elevation in risk for medium level exposure to both electric and magnetic fields. However, there is no consistent indication of increasing risk for increasing exposure to magnetic fields, within the three electric field exposure levels. For high exposure to both electric and magnetic fields, high exposure to electric and medium exposure to magnetic fields, and medium exposure to electric and high exposure to magnetic fields, the lower limit of the 95 percent confidence interval was above 1.0.

The joint effects of cumulative electric and magnetic field exposure were also evaluated for lung cancer (the findings are not tabulated here). There was a suggestion of increasing risk with increasing exposure to both electric and magnetic fields; for high exposure to electric and magnetic fields, the odds ratio was 1.87 (95 percent CI 0.77–4.53) (no interaction term) or 1.84 (95 percent CI 0.69–4.94) (model with interaction term).

TABLE 3. Odds ratios for exposure to cumulative electric fields among Ontario electric utility workers, 1970–1988

	Exposure level								
	0–171 V/m-years,* no. of cases	172–344 V/m-years				≥345 V/m-years			
		No. of cases	OR†	Adjusted OR‡	95% CI†	No. of cases	OR	Adjusted OR‡	95% CI
Site of a priori interest									
All hematopoietic malignancies	35	50	1.94	1.80	0.96–3.40	55	1.85	1.65	0.79–3.44
Non-Hodgkin's lymphoma	14	17	1.69	2.14	0.69–6.62	20	2.09	2.44	0.72–8.29
All leukemia	11	13	1.60	2.07	0.59–7.22	26	3.50	4.45	1.01–19.7
Acute nonlymphoid leukemia	4	6	3.67	9.99	0.58–172	10	4.66	7.89	0.43–143
Acute myeloid leukemia	3	3	1.88	9.60	0.21–438	7	3.00	24.53	0.55–1,098
Chronic lymphoid leukemia	3	6	1.25	1.25	0.07–21.2	10	2.53	7.18	0.31–169
Malignant brain tumors	12	4	0.42	0.57	0.10–3.17	8	0.68	0.99	0.16–6.24
Benign brain tumors	6	2	0.73	1.41	0.10–19.5	3	0.98	0.53	0.03–8.10
Malignant melanoma of the skin	22	18	1.51	1.10	0.40–3.06	18	1.21	0.87	0.30–2.48
Other sites									
Lip, buccal, and pharynx	19	24	0.68	0.47	0.13–1.72	24	0.70	0.35	0.07–1.88
Stomach	15	9	0.58	0.52	0.14–1.99	20	1.52	2.02	0.29–13.9
Colon	51	56	0.80	0.61	0.31–1.22	61	0.78	0.54	0.23–1.27
Prostate	51	100	1.23	1.16	0.67–2.01	93	1.19	1.17	0.62–2.22
Lung	57	99	1.37	1.20	0.66–2.17	107	1.89	1.46	0.75–2.84
All cancers	413	524	1.15	1.02	0.83–1.27	547	1.21	0.98	0.76–1.27

* Referent level.

† OR, odds ratio; CI, confidence interval.

‡ Adjusted for socioeconomic status, year of first hire in Ontario Hydro, and potential occupational confounders (non-Hodgkin's lymphoma: (2,4-dichlorophenoxy)acetic acid (2,4-D) and (2,4,5-trichlorophenoxy)acetic acid (2,4,5-T); leukemias: ionizing radiation, 2,4-D, 2,4,5-T, and benzene; brain cancer: ionizing radiation; melanoma: sunlight; lung cancer: ionizing radiation, asbestos, cadmium, and cadmium compounds).

The risk of leukemia in relation to the job titles held for ≥1 year is examined in table 6. Only for operators, for power line maintainers, and for technical, maintenance, and security workers is there an indication of an elevation in risk, but the numbers of cases and controls in each category are small. For job sites (table 7), there were also small numbers in each category, though there was an indication of increased risk in area offices, in hydroelectric, nuclear, and thermal generation stations, and in transformer stations.

DISCUSSION

The results of the present analysis have to be interpreted with caution. This is because the Ontario Hydro study was planned with the objective of contributing to a triutility study, and it was expected that only the combined data set would have sufficient statistical power to address the study objectives (25). However, because of the larger Ontario Hydro work force than that of Hydro Québec and the absence of person-years of experience of the workers who had left the corporation or retired in Electricité de France, the Ontario Hydro component of the joint study contributed nearly twice as many subjects as from Hydro Québec and almost as many as from Electricité de France. In addition, the Ontario Hydro component contributed the majority of the subjects with high level exposure to magnetic fields in the triutility analysis (25), as the exposures in France were lower than those in Canada.

The present analysis shows associations for all leukemia and its subtypes with increasing electric field exposure, with a dominant effect of electric field exposure on leukemia when both electric and magnetic field exposures are considered together. The paucity of numbers of cases and controls did not permit a similar analysis for the leukemia subtypes. The present analysis also confirms the triutility analysis (25) in showing associations for all leukemia, acute nonlymphoblastic leukemia, and acute myeloid leukemia with exposure to cumulative magnetic field exposure, when considered alone. However, these became nonsignificant after adjustment for socioeconomic status, year of hire, and potential occupational confounders, and it is possible that these odds ratios were elevated only because of the incomplete correlation between electric and magnetic field exposure ($r = 0.37$ for the leukemia cases and 0.47 for their controls).

Unlike magnetic fields, electric fields are significantly perturbed by the body of the worker wearing the

TABLE 4. Odds ratios for exposure to cumulative magnetic fields among Ontario electric utility workers, 1970–1988

	Exposure level								
	0–3.1 μT-years,* no. of cases	3.2–7 μT-years				≥7.1 μT-years			
		No. of cases	OR†	Adjusted OR‡	95% CI†	No. of cases	OR	Adjusted OR‡	95% CI
Site of a priori interest									
All hematopoietic malignancies	38	49	1.37	1.23	0.73–2.08	53	1.46	1.23	0.69–2.20
Non-Hodgkin's lymphoma	13	19	1.41	1.27	0.54–2.98	19	1.77	1.29	0.46–3.64
All leukemia	10	16	2.04	1.67	0.58–4.76	24	2.84	1.56	0.47–5.14
Acute nonlymphoid leukemia	3	6	3.04	1.93	0.27–13.7	11	5.02	2.87	0.42–19.8
Acute myeloid leukemia	0	5	1.00§	1.00§		8	4.31	3.81	0.31–48.9
Chronic lymphoid leukemia	4	6	1.22	0.49	0.06–4.24	9	1.62	0.25	0.01–4.63
Malignant brain tumors	7	7	1.11	1.27	0.32–5.41	10	1.33	2.36	0.52–10.8
Benign brain tumors	3	4	1.92	5.38	0.42–69.3	4	2.59	5.64	0.30–105
Malignant melanoma of the skin	21	19	0.95	0.96	0.42–2.20	18	1.06	1.05	0.38–2.86
Other sites									
Lip, buccal, and pharynx	21	19	0.70	0.47	0.16–1.32	27	0.96	0.68	0.23–2.02
Stomach	9	14	2.23	2.23	0.49–10.2	21	1.84	2.00	0.42–9.53
Colon	61	52	0.87	0.75	0.40–1.43	55	0.62	0.46	0.23–0.93
Prostate	72	78	0.93	0.93	0.57–1.54	94	0.96	0.91	0.54–1.55
Lung	63	94	1.36	0.93	0.56–1.54	106	1.96	1.22	0.69–2.15
All cancers	444	466	1.04	0.92	0.76–1.12	574	1.21	1.01	0.82–1.24

* Referent level.

† OR, odds ratio; CI, confidence interval.

‡ Adjusted for socioeconomic status, year of first hire in Ontario Hydro, and potential occupational confounders (non-Hodgkin's lymphoma: (2,4-dichlorophenoxy)acetic acid (2,4-D) and (2,4,5-trichlorophenoxy)acetic acid (2,4,5-T); leukemias: ionizing radiation, 2,4-D, 2,4,5-T, and benzene; brain cancer: ionizing radiation; melanoma: sunlight; lung cancer: ionizing radiation, asbestos, cadmium, and cadmium compounds).

§ Referent (as there were no cases in the 0–3-μT category).

TABLE 5. Odds ratios* for all leukemia for the interaction between electric and magnetic fields among Ontario electric utility workers, 1970–1988

Magnetic fields	No. of cases	No. of controls	Electric fields			
			OR†	95% CI†	OR‡	95% CI
0–171 V/m-years						
0–3.1 μT-years	4	46	1.00§		1.00§	
3.2–7 μT-years	6	15	1.16	0.40–3.40	4.84	0.89–26.3
≥7.1 μT-years	1	11	1.10	0.32–3.78	1.20	0.11–13.2
172–344 V/m-years						
0–3.1 μT-years	5	27	1.42	0.45–4.52	4.98	0.77–32.3
3.2–7 μT-years	2	20	1.65	0.34–8.02	1.24	0.10–15.0
≥7.1 μT-years	6	20	1.57	0.29–8.51	7.83	1.06–58.0
≥345 V/m-years						
0–3.1 μT-years	1	1	3.17	0.82–12.3	16.3	0.50–533
3.2–7 μT-years	8	25	3.69	0.65–20.8	11.3	1.52–84.3
≥7.1 μT-years	17	34	3.51	0.56–21.9	11.2	1.30–97.2

* Adjusted for socioeconomic status, year of first hire in Ontario Hydro, and potential occupational confounders (ionizing radiation, (2,4-dichlorophenoxy)acetic acid, (2,4,5-trichlorophenoxy)acetic acid, and benzene).

† OR, odds ratio; CI, confidence interval.

‡ Model includes terms for the interaction between electric and magnetic fields.

§ Referent for the odds ratios in this column.

monitor, so that the resultant reading is influenced by not only the ambient electric field strength and direction but also the wearing position of the monitor (normally at the waist in this study), the physical characteristics of the worker, and the body posture (e.g., standing, bending, arms extended). The larger

TABLE 6. Odds ratios for all leukemia cases and job title (ever held) among Ontario electric utility workers, 1970–1988

Job title	No. of cases	No. of controls	Odds ratio*	95% CI†
Clerk, professional, and manager‡	15	85	1.00	
Control maintainer/technician	3	3		
Customer service representative	1	4		
Foresters	0	7		
Inspector	0	7		
Meter reader	1	3		
Operators	5	20	3.34	0.48–23.0
Power line maintainer	16	42	1.89	0.60–5.92
Power maintenance electrician	1	6		
Stockkeeper	2	8		
Supervisors (technical and trade)	8	48	0.70	0.22–2.20
Truck driver	1	3		
Technical, maintenance, and security	13	48	2.37	0.56–10.1
Technician (other)	6	39	0.99	0.26–3.82
Protection and control technician	4	6		
Trade (general)	11	54	1.06	0.24–4.63

* Adjusted for duration of employment in job title.
† CI, confidence interval.
‡ Referent group.

TABLE 7. Odds ratios for all leukemia cases and job site among Ontario electric utility workers, 1970–1988

Job site	No. of cases	No. of controls	Odds ratio*	95% CI†
Heliport, administration, and inspection‡	6	34	1.00	
Area office	4	18	2.69	0.26–27.6
Control center	0	0		
Construction	18	65	1.07	0.29–4.00
District office	1	3		
Hydroelectric generation station	7	31	2.33	0.33–16.7
Nuclear generation station	5	20	2.91	0.18–46.2
Regional office	2	14	0.41	0.04–4.13
Service center	5	11		
Technical facility	0	1		
Thermal generation stations	6	23	2.05	0.26–16.1
Transformer station	7	20	4.00	0.64–24.8
Warehouse	2	3		

* Adjusted for duration of employment in job site.
† CI, confidence interval.
‡ Referent group.

uncertainties inherent in assessing electric field exposure relative to magnetic field exposure may translate to a greater extent of misclassification, when assigning workers to exposure groups, and thus would be expected to diminish the magnitude of the observed association. Thus, the associations that exist in practice may be even stronger than those reported in the present study.

A detailed analysis by job title and type of work location was performed. No significant associations were noted by job title or by work site, though there were some jobs and sites with suggestive increases in risk.

As cases were ascertained by record linkage to the Ontario Cancer Registry, there was no mechanism for identifying cases in subjects who might have left the province. Some confidence that this is not a major issue is gained from the fact that, for those who were retired, the standard mechanisms within Ontario Hydro identified deaths and the cause of death. We know of no reason why underascertainment of cases may have been biased with regard to exposure.

In the report on the triutility analysis (25), doubt was cast on the causality of the association of magnetic field exposure with leukemia, because it seemed to be mainly present in the Ontario Hydro component of the study and because there was no consistent evidence of an exposure-response relation. In the present analysis, however, an increasing risk of leukemia with increasing exposure to electric fields has been demonstrated.

The absence of an association with leukemia from exposure to magnetic fields in the other components of the triutility study data (25) requires comment. As already indicated, the numbers of cases and controls in Hydro Québec were substantially lower than for Ontario Hydro, and thus an association could easily have been missed by chance alone. The absence of an association in the Electricité de France data may be due to 1) more than 75 percent of their study population's being in the exposure category for magnetic fields below the median and 2) the absence of data on retired workers.

Further, there were differences in the way the job exposure matrix for electric and magnetic field exposure was constructed within Ontario Hydro compared with Hydro Québec and Electricité de France (25). In Hydro Québec and Electricité de France, decisions were made in advance on the likely high exposure job titles to be monitored. In Ontario Hydro, the workers monitored corresponded to those titles in the case-control data set, and job site information was included in the job exposure matrix. This showed that, for some workers with anticipated low exposure (such as professionals, managers, clerks, and storekeepers), if they worked in a site such as hydroelectric stations and transformer stations with high exposure in general, they also had high exposure. Thus, although in all three utilities the same measuring instrument was used and every effort was made to ensure that monitoring represented a typical worker performing his usual range of activities, there may have been greater opportunity for misclassification of exposure in the other two utilities than in Ontario Hydro. This supposition was confirmed by an analysis of Ontario Hydro data using a specially constructed data set that minimized job site information in the job exposure matrix and, thus, was more comparable to the process used in developing the job exposure matrix for Hydro Québec and Electricité de France, which showed lower odds ratios compared with the findings presented here. For example, the odds ratio of 1.56 for all leukemia with exposure to the upper tertile of magnetic fields in table 4 fell to 0.97 when site data were eliminated.

Our findings for leukemia are largely compatible with those in the published literature. A recent Swedish study (26) was anomalous in showing elevated risk only for chronic lymphoid leukemia. Although odds ratios were elevated for chronic lymphoid leukemia in the present study, the effect was mainly for electric fields and was less than for risks of acute nonlymphoid leukemia and its component acute myeloid leukemia. A case-control study of nonchronic lymphoid leukemia in a primarily retired population of American Telephone and Telegraph workers found nonsignificant increased risks compatible with those in the present study (27). There were similar findings in a study of Norwegian workers (28).

Two cohort studies of electric utility workers have recently been reported from the United States (29, 30) and one from Norway (31). The first study reported no increased risk for leukemia (29). However, as all "nonelectric workers" were grouped together for the purpose of exposure assessment, and exposures to "electric workers" were assigned on the basis of job title only, exposure assessment may have been substantially less precise than for the present study. The second study (30) also reported no excess risk for leukemia (except in a subset of "electricians") but did find an excess of brain tumors related to high level exposure to magnetic fields. An excess risk for astrocytomas was reported in the triutility analysis (25), but only a nonsignificant excess risk for malignant brain tumors with exposure to magnetic fields was found in the present analysis, with no risk from exposure to electric fields. The Norwegian study (31) was small (only 5,088 men) and did not involve measurements of electric or magnetic field exposure. There was an association of estimated magnetic field exposure with melanoma, but not with leukemia or brain tumors.

It is not clear why there should be a discrepancy among the studies. We may have failed to see a significant brain tumor association because of low power. The findings in table 4 are, however, compatible with those from the US (30) study. In the US (30) study, the inability to fully characterize leukemia cases by histologic type and differences in exposure assessment methods may account for their failure to find an association with leukemia. However, none of these studies developed a job exposure matrix with attention to job site. The present study suggests that failure to utilize job site information could lead to substantial misclassification of past exposure and, thus, attenuated associations.

In the present study, of the sites not of a priori interest, only for lung cancer was there a suggestion of association with exposure to electric and magnetic fields. An association has been noted between lung cancer and pulsed electromagnetic field exposure in the Hydro Québec and Electricité de France data combined (32). Pulsed electromagnetic field exposure has so far not been evaluated with Ontario Hydro data.

An issue that needs further exploration is the most biologically relevant exposure metric to use in these types of studies. Smith (33) has commented upon the nonlinear relations for peak exposure intensity and cumulative exposure, the former being generally associated with acute health effects and the latter being often used for chronic diseases. However, the relevant exposure metric will depend on the biologic process, especially the stage of carcinogenicity at which electric and magnetic fields act. Exposure metrics related to peak and intermittent exposures remain to be explored in the Ontario Hydro data.

In conclusion, this study confirms the previously observed associations between estimated exposure to magnetic fields and certain types of leukemia in the Ontario Hydro component of the triutility study (25). Uniquely, it demonstrates significant associations with cumulative electric field exposure and the occurrence of all leukemia, with suggestions that the risk may mainly relate to acute nonlymphoblastic leukemia and its component acute myeloid leukemia. Exposure-response relations are present for these associations. The findings from the study suggest that failure to incorporate job site may have resulted in misclassification in previous studies and that the associations of leukemia with magnetic field exposure noted in previous studies may have been driven by concomitant exposures to electric fields.

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