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ORIGINAL CONTRIBUTIONS

Cancer Risks Associated with Occupational Exposure to Magnetic Fields among Electric Utility Workers in Ontario and Quebec, Canada, and France: 1970–1989

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To determine whether occupational exposure to magnetic fields of 50–60 Hz was associated with cancer among electric utility workers, the authors used a case-control design nested within three cohorts of workers at electric utilities: Électricité de France–Gaz de France, 170,000 men; Ontario Hydro, 31,543 men; and Hydro-Québec, 21,749 men. During the observation period, 1970–1989, 4,151 new cases of cancer occurred. Each participant's cumulative exposure to magnetic fields was estimated based on measurements of current exposure of 2,066 workers performing tasks similar to those in the cohorts using personal dosimetry. Estimates were also made of past exposure based on knowledge of current loading, work practices, and usage. Workers who had more than the median cumulative exposure to magnetic fields (3.1 microtesla (μT)-years) had a higher risk for acute nonlymphoid leukemia (odds ratio (OR) = 2.41, 95% confidence interval (CI) 1.07–5.44). The same observation holds for acute myeloid leukemia (OR = 3.15, 95% CI 1.20–8.27). There was also an elevated risk for mean exposure above 0.2 μT (acute nonlymphoid leukemia, OR = 2.36, 95% CI 1.00–5.58; acute myeloid leukemia, OR = 2.25, 95% CI 0.79–6.46). However, there were no clear dose-response trends with increasing exposure and no consistency among the three utilities. Men whose cumulative exposure to magnetic fields was above the 90th percentile (15.7 μT-years) had an elevated risk for brain cancer (OR = 1.95, 95% CI 0.76–5.00) that was not statistically significant. No association with magnetic fields was observed for any of the other 29 types of cancer studied, including skin melanoma, male breast cancer, and prostate cancer. Controlling for potential confounding factors did not change the results. *Am J Epidemiol* 1994;139:550–72.

brain neoplasms; breast neoplasms; electromagnetic fields; leukemia; neoplasms; occupational diseases; occupational exposure

Since Samuel Milham (1) first reported an excess of leukemia among men working in "electrical occupations," scores of occupational studies have been published on the

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Abbreviations: CI, confidence interval; EDF, Électricité de France–Gaz de France; HQ, Hydro-Québec; μT, microtesla; OH, Ontario Hydro; OR, odds ratio; SES, socioeconomic status.

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putative association between cancer (mostly leukemia and brain cancer) and occupational exposure to electromagnetic fields of extremely low frequency. These studies have been the object of several literature reviews (2–6). In general, they have shown, with a great deal of inconsistency, a slight increase in the incidence of all leukemia and acute myeloid leukemia among electric workers.

Except for two recent papers (7, 8), these previous studies have been questioned on several design limitations. The most important has been the validity of exposure assessment. In most cases, exposure was entirely inferred through job titles. This was imprecise and believed to be the source of important misclassification. Another concern has been sample size. The great majority of studies have reported excesses of cancer based on small numbers of cases, often fewer than 10. The lack of controlling for exposure to other potential carcinogens present in the workplace has also been stressed. Many authors have concluded their articles by raising the possibility that the excess leukemia observed among workers in broadly defined electrical occupations could have been attributable to other carcinogens that they were unable to control for.

This study was designed to improve on previous studies by including a large number of workers and cancer cases, extensive and meticulous assessment of exposure to electromagnetic fields, and an assessment of exposure to chemical and physical agents encountered in the workplace. Furthermore, it addressed not only the few cancer types that have attracted the most attention so far, but extended its observation to all cancers.

The term "electromagnetic fields" corresponds to two different entities: electric fields and magnetic fields. The present article is concerned only with magnetic fields.

MATERIALS AND METHODS

Study base

This is a case-control study nested within three cohorts of electric utility workers. The study base consisted of all permanent male employees who had completed 1 full year of service at one of three electric utilities: Électricité de France–Gaz de France (EDF), France, and Ontario Hydro (OH) and Hydro-Québec (HQ), Canada. Because of specific characteristics peculiar to each utility, the study base varied somewhat for each of the utilities. At HQ, the cohort included all workers at work on January 1, 1970, and all new employees from 1970 to December 1988. At OH, the cohort comprised all men employed on January 1, 1973, and all new employees from 1973 until December 1988. The OH cohort also included men who left before 1973 but were on the pension roll at some time during 1970–1973. The EDF cohort included only active employees who were at work during 1978–1989 inclusively. The source population was estimated at 21,749 men from HQ, 31,543 men from OH, and an annual average of 120,000 men (170,000 men overall) from EDF (approximately 20 percent working on either gas or both electric and gas networks).

Cases and controls

Cases were men whose first diagnosis of cancer was made during the observation period. For those with more than one cancer, only the first cancer was considered. At HQ and OH, the observation period ended either at death or on December 31, 1988. At EDF, it was not possible to follow up workers after they terminated employment at the utility, so the observation period ended either on the date of termination of employment or on December 31, 1989; consequently, the EDF cases included only those with cancer diagnosed during the active work life of the employee. This means that cases at EDF were younger, the retirement age being between the ages of 55 and 60 years, depending on job type.

In Quebec, the search for cases was conducted through several sources: the companies' medical files, the Quebec Tumour Registry, and death certificates. Cases were validated with hospital records when necessary. In Ontario, all cases were identified

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through a linkage of the OH cohort with the Ontario Cancer Registry. The high quality of the information held by this agency was judged sufficient to render validation of OH cases through other sources unnecessary. In France, cases were identified through a company file called *La banque de données épidémiologiques* (9). This is a comprehensive data bank that keeps records of all employee leaves of absence due to sickness for benefits and control purposes. Cases were validated through consultation with physicians at the health centers, hospital records, and, in some instances, the treating physicians.

Controls were other employees from the same utility matched to the case on year of birth. For each case, a "risk set" was generated comprising all study participants who were born in the same year, were alive, and were members of the cohort at the date of diagnosis of the case. Controls were selected at random from these "risk sets." A man selected as a control could become a case later on in the study. Cancers were divided into two categories: 1) those for which an association with electromagnetic fields had previously been reported in the literature (cancers of the hematopoietic system, brain cancers, and skin melanoma), which were considered as being of a priori interest and for which our study served as a hypothesis test, and 2) all other cancers, which were considered as being of a posteriori interest and for which we were exploring rather than confirming a putative association. For cancers defined a priori as of special interest, the case-control ratio was 1:4; for the other cancers, the ratio was 1:1.

Exposure assessment

Since the number of jobs ever held by study participants was enormous, and since the majority were no longer working at the time of the measurement campaigns, it was not possible to proceed to a direct measurement of the exposure of each case and control. Exposure was therefore assessed indirectly by combining information from the workers' occupational histories and estimates of exposure for each job they held.

For each case and each control, a detailed occupational history was secured from administrative files held by the companies. The information collected included, for each job held: job title, starting date, ending date, and location (site). Whenever a case's occupational history could not be located or reconstructed, the case was deleted. A control whose occupational history was unavailable was deleted if other controls were available (for a priori cancers); otherwise, the control was replaced.

Assessment of magnetic fields

Because of differences peculiar to the work environments and work practices at each of the three utilities, it was decided that each utility would, upon guidance and standardization from the study coordinator, provide an estimate of exposure for each of its study participants. The means used to arrive at these estimates were allowed to differ from one utility to the other, but the final estimate was to reflect each participant's real exposure.

Assessment of magnetic fields was carried out in two steps: measuring current levels of exposure and estimating past levels. Current exposure to magnetic fields of 50 Hz in France and 60 Hz in Canada was measured using the Positron model 378108 personal exposure monitor (Positron Industries, Montreal, Quebec, Canada). The IREQ meter (Institut de Recherche d'Hydro-Québec, Montreal, Quebec, Canada) (10), a prototype version of the Positron meter, was also used for approximately 9 percent of the measurements. In total, 2,066 workers underwent exposure measurements: 829 at EDF, 771 at OH, and 466 at HQ. The meter was worn on the worker's belt or in a shirt pocket for a full 5-day work week. Simultaneously, the worker filled out a diary recording the type of activities performed, their timing, their location, voltages, currents, and work techniques; main activities outside work during the measurement period were also recorded.

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From these readings and diaries, the mean exposure (time-weighted average) during the week's working hours was extracted.

Although measurements were recorded for the off-work hours, they were not relevant to the design of the study, and only measurements made during working hours were used in the current analysis. To allow calculation of the cumulative exposure of study participants, job exposure matrices were created separately for each utility. In HQ and EDF, the matrices comprised 32 and 37 rows, respectively. The rows were derived by utility hygienists, occupational physicians, and health and safety committees based on a priori grouping of job titles with similar expected exposure levels, sometimes subdivided to reflect expected regional or site-specific differences in exposure. Workers were sampled for inclusion in the measurement campaign to achieve a representative sample of all workers in each category. The index for each job category used in this report was the arithmetic mean of the weekly arithmetic means of all workers within the category.

The procedure for arriving at a job exposure matrix was somewhat different for OH. All job titles actually held by cases and controls were blindly identified. Measurements were made for 260 job titles. These jobs were first grouped into 110 categories based on similarity of types of activities and environments expected to predict exposure. These were further regrouped into 17 broad groups. This regrouping was made partially on the basis of long-term similarity of environment and partially on the basis of similarity in the dosimetry results using statistical significance criteria following regression tree methods (11) implemented in the KnowledgeSEEKER software (12). Finally, the same software was used to identify, for each of the 17 broad job categories, whether differences in work location (e.g., area office, service center, hydraulic generating station) were sufficient to warrant using different estimates for different locations. This resulted in dividing 11 of the 17 broad groups to form a total of 48 location-specific estimates in the final job exposure matrix. However, information on work location was unavailable for about 20 percent of the work records, so that generic estimates for the 11 split groups were also retained, giving a total of 65 estimates.

To assess past exposure, we interviewed utility personnel and examined system records regarding changes in power systems, work techniques, exposure sources, work locations, and duration of work periods. This information was used to estimate adjustment factors that were applied for different periods back to 1945. The method used to derive adjustment factors differed somewhat among the three utilities. At EDF, these factors were arrived at through expert judgments, taking into consideration changes in the production, transportation, and distribution systems, modifications in job-task duration, lengths of work shifts, and modes of operation. At OH, adjustment factors for five types of site or facility were derived using system records of loads, operating voltages, and circuit lengths. At HQ, estimates of current durations and intensities of exposures for tasks comprising present jobs were obtained from meter measurements. These were then adjusted using information on changes in the power system, task duration, and working techniques. To assess the effect of the differences in arriving at correcting factors for past exposures, we analyzed the results with and without the use of these correcting factors. The results were not substantially modified by doing so.

Confounders

Estimates of exposure were made for each chemical and physical agent listed as carcinogenic or possibly carcinogenic in categories 1, 2A, and 2B of the International Agency for Research on Cancer (13): and in categories A1 and A2 of the American Conference of Governmental Industrial Hygienists (14). These estimates were arrived at through expert judgments and consultation with longstanding utility employees. Historical changes over time were also taken into account. For each chemical, a cumula-

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tive exposure index was computed for each participant using an approach not dissimilar to the approach used for estimating magnetic field exposure, namely, calculating the sum of the products of the exposure estimates for each job (expressed as a time-weighted average normalized to the 1990–1991 threshold limit values set by the American Conference of Governmental Industrial Hygienists) and duration of time in that job. For chemicals for which information was insufficient to assess a time-weighted average exposure, exposure was assessed on a simple duration (percentage of time) scale, or simply as present or absent. For ionizing radiation, the cumulative individual dose in sieverts was obtained directly from each company's ionizing radiation surveillance program.

Smoking information was available for HQ workers only. Since 1970, this had routinely been recorded in medical files at the time of the periodic examination under the format of smoking status (current smoker, nonsmoker) and the number of cigarettes smoked per day. It was collected for 55 percent of the HQ participants and was compiled for the period before diagnosis only.

Socioeconomic status (SES) at the time of hiring was assessed separately at each utility, based on the first job title held. At HQ and OH, ad hoc classification systems were designed. At EDF, a standard classification was used: *Nomenclature des professions et des catégories socio-professionnelles* (15). The three classifications were then collapsed into a single, five-category scale.

Analysis

For each participant, an overall time-weighted arithmetic mean exposure to magnetic fields was calculated as the arithmetic mean of the overall time-weighted arithmetic mean exposure in each job, weighted by the duration of time in each job. Cumulative exposure (in units of microtesla (μT)-years) was defined as the product of this mean exposure and the duration of employment (1 μT = 10 milligauss).

To allow for the possibility that it is the most recent exposure that carries the risk or, conversely, that the risk appears only long after exposure, time-weighted average and cumulative exposure were also calculated for three periods: the 5 calendar years immediately preceding diagnosis (or an analogous period for controls), the 20 years preceding diagnosis, and 20 years or more before diagnosis.

To respect the matched design of the study and allow for adjustment for possible confounding factors, we estimated odds ratios and their 95 percent confidence intervals by conditional logistic regression (16) using the EPICURE program (17). For infinite odds ratios, we obtained exact lower 95 percent confidence limits through stratified analysis using the EGRET package (18). Where there were fewer than 10 cases overall or 10 workers (cases and controls) in the exposed or "baseline" group, the odds ratio estimates were very imprecise and are not shown. The confidence intervals and p values of certain odds ratios of particular interest were recalculated using a computationally intensive exact conditional logistic regression (19). Where p values are given, they are from two-sided tests.

Participants were divided into four groups by exposure to magnetic fields, with group boundaries at the 50th, 75th, and 90th percentiles of each exposure index obtained using all participants in the study. Odds ratios were estimated for each group and for the top three groups combined ($\geq$median), relative to the lowest (<median). Trends in risk were assessed by fitting in the logistic regression model a numerical variable equal to the mean exposure in the exposure group of the participant. Consistency of the associations across utilities was tested for using the score test for interaction (16).

SES was found to be strongly associated with cancer risk in general and with most specific sites of cancer. SES was routinely adjusted for in the analyses. Because coding into SES categories was not strongly standardized across utilities and because the pat-

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tern of risk varied somewhat by utility, adjustment allowed for separate SES effects in each utility by entering the utility by the SES interaction term in the regressions.

Confounding by chemicals was adjusted for by entering the cumulative exposure indices into the logistic regression models. As for SES, to allow for differences between utilities in the scale or accuracy of measurement, the chemical was entered with the utility by the chemical interaction term.

RESULTS

Table 1 shows, for a selection of jobs in each utility, the arithmetic mean magnetic field (as used in the job exposure matrix) together with the number of work weeks and the standard deviation between the means of workers in that job. For EDF and HQ, we also give the exact 95 percent confidence interval for the mean, assuming a lognormal distribution (20). We did not do this for OH, because the method of deriving the means (using regression tree grouping algorithms and using days rather than weeks as the basis for means) would make calculation and interpretation of confidence intervals problematic. The geometric means of each worker's dosimeter readings are also given to allow evaluation of the extent to which our results depend on the choice of the arithmetic mean as the index. Finally, we show the adjustment factor used to calculate 1950 estimates from current estimates.

The distribution of basic demographic and employment variables (table 2) reflects the parameters of the study design and their differences between utilities. Thus, OH, which included men on the pension roll in 1970, shows the lowest year of birth and start of employment, and the highest age at diagnosis. Conversely, EDF, in which follow-up did not begin until 1978 and did not continue after the termination of employment, shows the opposite pattern. In all utilities, the median length of employment was high (23.7–27.0 years), although at EDF, not much of this was more than 20 years before diagnosis. Differences between utilities in mean and cumulative exposure to magnetic fields reflect the different estimated levels of exposure.

Summary odds ratios for each of 31 groups of cancer by site and cumulative exposure to magnetic fields, adjusted for SES, are given in table 3. Leukemia was subdivided into four categories as proposed by Linet (21): chronic lymphoid, chronic myeloid, acute lymphoid, and acute nonlymphoid. Acute myeloid leukemia was also analyzed separately. Brain cancer was divided into its two major cell types, astrocytoma and glioblastoma. Benign brain tumors were analyzed separately. There was a statistically significant elevation ($p < 0.05$) in two of the odds ratios: that for acute nonlymphoid leukemia (or acute myeloid leukemia) ($\geq$median) and that for astrocytoma ($\geq$90th percentile). With the existing software, reanalysis of these using exact logistic regression was possible only for acute myeloid leukemia, for which the odds ratio changed little (to 3.16, 95 percent confidence interval (CI) 1.11–9.24). The odds ratio for astrocytoma was based on small numbers and was highly dependent on the specific adjustment for SES; adjustment by a simple white-collar/blue-collar variable reduced the odds ratio to 1.53 (95 percent CI 0.38–6.25).

For all cancers combined, leukemia (and specifically chronic lymphoid leukemia and acute nonlymphoid leukemia), brain cancer (specifically astrocytoma and glioblastoma) and melanoma, we report more detailed results. Dividing the participants by utility (table 4) showed that the association of leukemia with magnetic fields was strongest at OH, present but weaker at EDF, and not apparent at all at HQ. In this table, odds ratios and confidence intervals for leukemia and astrocytoma were estimated wherever feasible with exact logistic regression, and therefore are given regardless of the number of cases. The difference between utilities was statistically significant for all leukemia combined ($p = 0.02$), according to a score test, although the exact confidence intervals

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TABLE 1. Mean exposures to magnetic fields for selected jobs at electric utilities in Ontario and Quebec, Canada, and France: 1970–1989

Utility* and job title	No. of weeks†	Mean exposure (μT)‡	95% CI‡	SD§ (μT)	Geometric mean (μT)	95% CI	Geometric SD‖	Adjustment factor¶
			Generation					
Hydroelectric								
HQ, operator	11	1.56	0.94–4.13	1.21	0.67	0.37–1.20	2.72	1.07
HQ, maintenance mechanic	24	0.77	0.45–1.19	1.19	0.18	0.13–0.25	2.30	1.00
OH, operator	13	5.39		10.21	0.44		4.58	1.00
OH, general trades	8	2.06		1.65	0.31		1.91	1.00
EDF, operations and maintenance, <100 MW station	20	1.38	0.68–6.33	1.96	0.11	0.06–0.21	3.95	2.00
EDF, operations and maintenance, >100 MW station	29	0.62	0.45–0.90	0.70	0.09	0.07–0.11	1.81	NA#
Nuclear								
HQ, operator	17	0.13	0.11–0.15	0.03	0.05	0.04–0.06	1.50	NA
HQ, equipment electrician	6	0.19	0.12–0.40	0.09	0.05	0.04–0.06	1.23	NA
OH, operator	7	0.26		0.22	0.07		1.61	NA
OH, control maintainer	7	0.20		0.10	0.08		1.45	NA
EDF, mechanics	46	0.29	0.21–0.40	0.30	0.06	0.05–0.08	2.39	NA
EDF, operator (all types)	14	0.23	0.16–0.43	0.17	0.07	0.05–0.09	1.74	NA
EDF, electrician	10	1.12	0.62–4.64	1.11	0.12	0.06–0.23	2.80	NA
Thermoelectric								
HQ, operator, diesel generator	11	0.32	0.26–0.42	0.15	0.12	0.09–0.17	1.80	1.00
OH, operator	15	0.45		0.32	0.12		2.58	1.00
OH, control maintainer	10	0.93		1.00	0.14		2.57	1.00
EDF, mechanics (includes some old nuclear plants)	27	0.22	0.17–0.29	0.17	0.06	0.05–0.08	2.01	1.00
EDF, operator (includes some old nuclear plants)	19	0.32	0.26–0.42	0.17	0.09	0.07–0.12	1.92	1.00
			Transmission and distribution					
Transmission, overhead lines								
HQ, transmission lineman	18	0.60	0.44–0.90	0.39	0.08	0.06–0 10	1.81	1.05
EDF, transmission lineman, dead line	20	0.31	0.22–0.46	0.28	0.05	0.04–0.08	2.10	0.33
EDF, transmission lineman, live line	10	0.53	0.28–2.58	0.49	0.07	0.04–0.12	2.16	NA
Transmission, underground lines								
HQ, transmission cable splicer	12	1.79	1.13–4.09	1.35	0.24	0.16–0.35	2.02	NA
EDF, transmission cable splicer	15	1.10	0.75–3.26	0.85	0.10	0.07–0.15	2.13	0.33

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TABLE 1. Continued

Utility* and job title	No. of weeks†	Mean exposure (μT)‡	95% CI‡	SD§ (μT)	Geometric mean (μT)	95% CI	Geometric SD‖	Adjustment factor¶
Substation: maintenance								
HQ, equipment electrician, <735 kV	29	2.36	1.12–3.74	4.45	0.24	0.17–0.33	2.58	0.68
HQ, equipment electrician, 735 kV	22	1.78	1.45–2.30	0.87	0.54	0.40–0.71	1.99	NA
OH, power maintenance electrician	32	1.06		1.21	0.26		2.61	0.86
OH, general tradesman	7	0.49		0.44	0.14		4.05	0.27
EDF, transmission substation maintenance	30	1.83	0.91–3.64	4.06	0.17	0.11–0.27	3.31	1.00
EDF, distribution substation maintenance	22	0.84	0.64–1.26	0.52	0.12	0.09–0.16	1.96	0.24
Substation: operations								
HQ, mobile operator (all types of substation)	16	1.17	0.76–2.44	1.08	0.23	0.15–0.35	2.39	0.53
HQ, fixed operator (735 kV substations only)	12	1.78	1.00–4.44	1.88	0.76	0.41–1.39	2.90	1.00
OH, operator	25	1.49		3.11	0.44		2.53	0.27
EDF, transmission substation operations (includes some maintenance)	54	0.74	0.63–1.19	0.53	0.15	0.12–0.20	2.69	1.00
Substation: protection and control technician								
HQ, technicians, automatic controls and relays	18	1.60	0.89–6.10	1.88	0.21	0.14–0.32	2.55	0.89
OH, protection and control technician	16	1.94		2.15	0.64		2.39	0.27
EDF, transmission, electrical controls	44	0.43	0.33–0.85	0.44	0.06	0.05–0.09	2.79	1.00
EDF, distribution and telecommunications electrical controls	11	1.34	0.39–12.98	2.80	0.07	0.03–0.13	3.07	0.24
Distribution, overhead lines								
HQ, distribution lineman, contact and hotstick	39	0.37	0.26–0.50	0.46	0.06	0.05–0.07	1.75	0.91
HQ, distribution lineman, contact	24	0.83	0.60–1.45	0.63	0.13	0.11–0.15	1.49	0.79

(*Table 1 continues next page.*)

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TABLE 1. Continued

Utility* and job title	No. of weeks†	Mean exposure (μT)‡	95% CI‡	SD§ (μT)	Geometric mean (μT)	95% CI	Geometric SD‖	Adjustment factor¶
OH, power line maintainer (includes 20% transmission)	84	0.52		0.87	0.07		2.58	0.42
EDF, distribution lineman, live line, hotstick	11	0.09	0.06–0.18	0.06	0.02	0.01–0.03	1.95	NA
EDF, distribution lineman, live and dead line	43	0.21	0.17–0.30	0.18	0.04	0.03–0.04	1.96	0.10
Distribution, underground lines								
HQ, distribution cable splicer	18	1.87	1.17–5.44	1.83	0.12	0.08–0.17	2.16	0.80
EDF, distribution cable splicer	5	0.20	0.15–0.33	0.07	0.04	0.04–0.05	1.27	0.25
Meter readers and installers								
HQ, meter reader	14	0.17	0.13–0.24	0.08	0.05	0.04–0.06	1.48	1.00
HQ, meter installer	10	0.42	0.23–1.19	0.40	0.08	0.06–0.09	1.36	0.54
OH, meter reader	16	0.15		0.13	0.05		1.41	0.27
OH, customer service representative	27	0.20		0.15	0.07		1.97	0.25
EDF, meter installer, low voltage	10	0.30	0.14–2.28	0.33	0.04	0.02–0.07	2.42	0.25
			Other					
Blue-collar								
HQ, vehicle and general mechanics, stockkeeper and toolkeeper	15	0.15	0.10–0.31	0.11	0.03	0.03–0.03	1.89	1.00
OH, truck driver	5	0.14		0.07	0.05		2.06	0.29
OH, stockkeeper	20	0.50		0.34	0.15		2.48	0.44
EDF, inspector	11	0.17		0.09	0.07		1.27	0.29
EDF, mainly gas workers	15	0.19	0.12–0.52	0.19	0.03	0.02–0.05	2.82	0.25
White-collar								
HQ, office workers	24	0.16	0.11–0.23	0.22	0.06	0.05–0.06	2.04	1.00
OH, clerk	38	0.22		0.29	0.09		2.25	0.32
OH, professional/ manager	94	0.20		0.26	0.08		2.20	0.35
EDF, office workers	102	0.13	0.11–0.15	0.10	0.04	0.04–0.05	2.47	0.25

* HQ, Hydro-Québec; OH, Ontario Hydro; EDF, Électricité de France–Gaz de France.
† Number of work weeks measured.
‡ μT, microtesla; CI, confidence interval.
§ SD, standard deviation between means of workers in each job.
‖ Geometric standard deviation between geometric means of each worker's dosimeter readings.
¶ Adjustment factors used to calculate 1950 estimates from current estimates.
# NA, not applicable, as this job did not exist in 1950.

suggest that the odds ratios might in fact be compatible. No other variation of odds ratios by utility approached statistical significance, but the numbers were often too few for meaningful interpretation of results for separate utilities.

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TABLE 2. Demographic, employment, and exposure variables for study participants* at electric utilities in Ontario and Quebec, Canada, and France: 1970–1989

Variable	Hydro-Québec (n = 1,997)			Ontario Hydro (n = 3,552)			Électricité de France–Gaz de France (n = 4,708)			Total (n = 10,257)		
	Median	LQ†	UQ†	Median	LQ	UQ	Median	LQ	UQ	Median	LQ	UQ
Year of birth	1923	1915	1932	1918	1909	1927	1935	1930	1942	1929	1918	1937
Year of diagnosis	1982	1978	1986	1982	1978	1986	1983	1980	1986	1983	1979	1986
Year of starting employment	1953	1945	1962	1949	1945	1961	1959	1954	1966	1956	1948	1965
Age at diagnosis (years)	58.5	49.1	66.7	63.9	55.3	72.2	48.7	41.7	52.5	53.0	45.8	63.2
If not employed at diagnosis:												
Year of termination of employment	1978	1973	1983	1973	1968	1978				1976	1970	1982
Years between termination of employment and diagnosis	5	3	9	8	4	13				6	3	11
Years from starting employment to diagnosis of case	29	19	38	32	21	39	24	18	29	27	19	34
Years of employment until diagnosis of case‡												
All	27.0	17.6	34.1	25.8	15.9	33.0	23.7	17.4	28.6	24.7	16.9	31.0
The 5 years preceding diagnosis	4.0	0.5	4.4	2.0	0.0	4.3	4.4	4.2	4.7	4.2	2.1	4.6
The 20 years preceding diagnosis	9.4	0.0	18.0	11.8	1.2	18.8	4.2	0.0	9.3	7.0	0.0	13.8
≥20 years before diagnosis	16.4	11.3	19.2	13.2	7.6	18.4	19.2	17.1	19.6	18.0	11.1	19.4
Exposure to magnetic fields§												
Mean (μT)	0.19	0.16	0.45	0.22	0.13	0.45	0.10	0.08	0.15	0.16	0.09	0.30
Cumulative (μT-years)	6.34	3.63	11.83	4.91	2.62	9.10	2.21	1.70	3.07	3.15	1.97	6.90

* Percentage of cases employed at diagnosis: Hydro-Québec, 56.9%; Ontario Hydro, 40.5%; Électricité de France–Gaz de France, 100.0%; all three cohorts combined, 71.0%

† LQ, lower quartile; UQ, upper quartile.

‡ Or until diagnosis of the matched case (for controls).

§ Until diagnosis of the case or, for controls, of the matched case.

Odds ratios were further adjusted for exposure to chemicals selected on the basis of existing knowledge of risk factors for each cancer site, namely, benzene, gasoline, paint, solvents, and ionizing radiation for leukemia and its subcategories; sunlight and ionizing radiation for melanoma; and ionizing radiation for brain cancer and its subcategories. They were expressed as the cumulative index, entered as a numerical variable. There appeared to be little confounding by chemicals, as the odds ratios changed little on adjustment.

To calculate odds ratios according to the time of exposure in relation to diagnosis (table 5), we excluded participants employed for less than a minimum part of the period in question: for the period of the 5 years immediately preceding diagnosis, those employed for less than 4 years; for the periods 20 years before diagnosis and 20 years or more before diagnosis, those em-

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TABLE 3. Adjusted odds ratios* for cancer among electric utility workers in Ontario and Quebec, Canada, and France, by cumulative exposure to magnetic fields: 1970–1989

Cancer site†	Exposure group									
	<Median‡		≥Median				≥90th percentile‖			
	No of controls	No. of cases	No of controls	No. of cases	OR	95% CI§	No. of controls	No. of cases	OR	95% CI
Sites of a priori interest										
All cancers (140–208, 225)	3,135	1,993	2,971	2,158	1.01	0.91–1.13	582	443	1.01	0.86–1.20
All hematopoietic cancers (200–208)	935	221	748	212	1.25	0.94–1.68	138	35	1.12	0.70–1.77
Non-Hodgkin's lymphoma (200, 202)	337	79	285	81	1.22	0.77–1.94	54	14	1.09	0.52–2.28
All leukemia (204–208)	307	70	239	70	1.54	0.90–2.63	41	13	1.75	0.77–3.96
Chronic lymphoid (204.1)	68	17	88	24	1.48	0.50–4.40	21	6	1.71	0.44–6.66
Chronic myeloid (205.1)	54	16	39	8	0.61	0.18–2.05	1	0		
Acute lymphoid (204.0)	43	10	12	4	2.07	0.12–35.25	2	1		
Acute nonlymphoid (205.0, 205.3, 205.9, 206.0, 207.0, 207.2, 207.8, 208.0, 208.9)	140	27	98	33	2.41	1.07–5.44	17	6	2.52	0.70–9.09
Acute myeloid (205.0, 205.9)	112	21	74	26	3.15	1.20–8.27	13	4	2.68	0.50–14.50
Hodgkin's disease (201)	210	52	97	27	1.33	0.65–2.70	18	4	1.17	0.32–4.24
Multiple myeloma (203)	81	20	127	34	1.06	0.44–2.53	25	4	0.58	0.14–2.32
Malignant brain cancer (191)	250	60	165	48	1.54	0.85–2.81	36	12	1.95	0.76–5.00
Astrocytoma (9400, 9401, 9411, 9421)¶	107	29	53	12	0.97	0.34–2.80	13	5	12.29	1.05–143.5
Glioblastoma (9440, 9441)¶	71	17	65	18	1.33	0.46–3.80	13	3	0.81	0.17–3.91
Other (9380, 9391, 9450, 9470, 9490)¶	35	7	19	7	∞	0.96–∞	5	1		
Unknown (8000, 8010, 8260, 9990, 9999)¶	37	7	28	11	2.82	0.58–13.74	5	3		
Benign brain cancer (225)	82	17	57	19	2.31	0.79–6.74	10	4	1.62	0.35–7.59
Melanoma (172, 190.6)	175	52	226	54	0.86	0.49–1.48	38	10	1.03	0.41–2.58
Other cancer sites										
Lip, buccal cavity, and pharynx (140–149)	288	277	143	154	1.07	0.76–1.50	30	23	0.76	0.40–1.43
Stomach (151)	63	57	67	73	0.88	0.45–1.75	7	18	2.16	0.66–7.04
Colon (153)	132	145	203	190	0.76	0.51–1.14	37	34	0.70	0.38–1.31
Rectum, anus, etc. (154)	71	72	121	120	0.78	0.41–1.47	28	31	0.88	0.39–1.96

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TABLE 3. Continued

Cancer site†	Exposure group									
	<Median‡		≥Median				≥90th percentile‖			
	No. of controls	No. of cases	No. of controls	No. of cases	OR	95% CI§	No. of controls	No. of cases	OR	95% CI
Other cancers of the gastrointestinal tract (150–159, excluding the three listed above)	173	158	144	159	0.99	0.64–1.53	26	36	1.46	0.73–2.94
Lung (162)	350	322	422	450	0.92	0.70–1.22	78	93	1.00	0.67–1.51
Other respiratory and thoracic cancers (160–161, 163–165)	108	114	79	73	0.78	0.46–1.34	16	14	0.68	0.29–1.59
Other cancers of the bone and connective tissue (170–175, excluding 172)	36	35	25	26	1.28	0.41–3.97	2	3		
Prostate (185)	114	99	243	258	1.30	0.87–1.95	67	65	1.18	0.70–2.00
Other cancers of the male genital tract (186–187)	87	87	29	29	0.97	0.40–2.33	4	4		
Urinary tract (188–189)	146	145	204	205	0.87	0.58–1.31	43	38	0.77	0.43–1.38
Unknown primary site (196–199)	87	89	64	62	0.79	0.42–1.47	20	15	0.57	0.23–1.44
Other solid tumors (190, 192–195, excluding 190.6)	38	43	31	26	0.70	0.26–1.89	2	8	5.00	0.44–57.06

* The odds ratios (OR) compare the indicated group of participants with the baseline group (exposure less than the median) and are adjusted for socioeconomic status.

† The classification numbers in parentheses are from the *International Classification of Diseases, Ninth Revision*, unless otherwise noted.

‡ Median exposure = 3.1 microtesla (μT)-years.

§ CI, confidence interval.

‖ The 90th percentile of exposure = 15.7 μT-years.

¶ Classification numbers from the *International Classification of Diseases for Oncology*.

ployed for less than 10 years. This was to avoid a "baseline" group composed mainly of participants who were employed at the utility little or not at all during the time in question, and who would therefore possibly be selected by factors related to health. The fourth row of odds ratios in the table for each site is by total cumulative exposure, as in table 3, but after participants who worked at the utility for a total of less than 10 years had been excluded. The high odds ratios for astrocytoma in participants above the 90th percentile of exposure in the 20 years before diagnosis and overall were based on small numbers. The association between exposure above the median and acute myeloid/acute nonlymphoid leukemia was not apparent for exposure in the 5 years immediately preceding diagnosis. The excess acute myeloid leukemia was most pronounced in participants exposed 20 years or more before diagnosis.

In table 6, we show the estimated odds ratios for each of the four cumulative exposure groups (<median, median–75th percentile, 75th–90th percentiles, and ≥90th percentile). Also shown are estimates of linear trends in odds ratios across these groups. These have been scaled so that the odds ratio presented is the one predicted for a participant with exposure equal to the mean of that in the top group relative to that of a participant with exposure equal to the mean of the bottom group. The trend for astrocytoma is due entirely to the high odds ratio in the highest exposure group, which is based on small numbers and, as with the overall re-

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TABLE 4. Adjusted odds ratios* for selected cancers among electric utility workers in Ontario and Quebec, Canada, and France, by cumulative exposure to magnetic fields and utility: 1970–1989

Site and utility†	Exposure group									
	<Median‡		≥Median				≥90th percentile‖			
	No. of controls	No. of cases	No. of controls	No. of cases	OR	95% CI§	No. of controls	No. of cases	OR	95% CI
All cancers										
HQ	289	129	934	645	1.13	0.85–1.50	206	151	1.17	0.81–1.68
OH	683	438	1,397	1,034	1.00	0.84–1.19	265	228	1.09	0.85–1.39
EDF	2,163	1,426	640	479	0.99	0.84–1.15	111	64	0.77	0.55–1.09
All leukemia										
HQ	16	6	79	18	0.29¶	0.04–1.75	12	4	0.45¶	0.04–3.83
OH	68	9	104	36	3.14¶	1.12–9.74	21	6	3.55	0.88–14.26
EDF	223	55	56	16	1.39¶	0.61–3.08	8	3	1.89	0.46–7.78
Chronic lymphoid leukemia										
HQ	6	3	34	7	0.25¶	0.02–2.56	8	2	0.27¶	0.02–4.22
OH	20	4	45	14	2.14	0.39–11.64	9	3	3.67¶	0.40–50.07
EDF	42	10	9	3	4.79¶	0.45–70.57	4	1	2.82¶	0.04–67.95
Acute nonlymphoid leukemia										
HQ	4	1	28	77	0.75¶	0.00 to >100	3	2	0.14¶	0.00 to >100
OH	29	2	43	16	6.24¶	0.95–77.49	10	3	8.37¶	0.46 to >100
EDF	107	24	27	10	1.78¶	0.57–5.39	4	1	1.42¶	0.03–16.15
Acute *myeloid* leukemia										
HQ	1	0	23	6	≠		3	2	≠	
OH	18	0	30	12	37.76¶	3.51 to >100	7	2	16.88¶	0.76 to >100
EDF	93	21	21	8	1.70¶	0.49–5.54	3	0	1.48¶	0.00–14.90
Malignant brain cancer										
HQ	25	6	69	18	1.60	0.38–6.82	21	6	1.68	0.29–9.67
OH	33	7	57	17	1.85	0.53–6.49	9	4	5.45	0.59–50.59
EDF	192	47	39	13	1.42	0.65–3.10	6	2		
Astrocytoma										
HQ	10	2	18	5	≠		8	3	≠	
OH	8	2	19	5	≠		4	1	≠	
EDF	89	25	16	2	0.43¶	0.08–2.16	1	1	4.04¶	0.05 to >100
Glioblastoma										
HQ	9	2	34	9	1.50	0.16–14.41	7	2		
OH	7	2	16	4			1	0		
EDF	55	13	15	5	1.07	0.29–3.90	5	1		
Melanoma										
HQ	21	5	51	13	1.37	0.30–6.31	14	5	3.98	0.44–36.01
OH	72	22	138	35	0.93	0.44–1.96	17	4	0.88	0.24–3.25
EDF	82	25	37	6	0.58	0.20–1.67	7	1		

* The odds ratios (OR) compare the indicated group of participants with the baseline group (exposure less than the median) and are adjusted for socioeconomic status.
† HQ, Hydro-Québec; OH, Ontario Hydro; EDF, Électricité de France–Gaz de France.
‡ Median exposure = 3.1 microtesla (μT)-years.
§ CI, confidence interval.
‖ The 90th percentile of exposure = 15.7 μT-years.
¶ Estimated by exact logistic regression.
≠ Undetermined, estimated by exact logistic regression.

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TABLE 5. Adjusted odds ratios* for selected cancers among electric utility workers in Ontario and Quebec, Canada, and France, by cumulative exposure to magnetic fields and time of exposure in relation to diagnosis: 1970–1989

Cancer site and time of exposure to magnetic fields (years) relative to diagnosis	Exposure group									
	<Median		≥Median				≥90th percentile			
	No. of controls	No. of cases	No. of controls	No. of cases	OR	95% CI†	No. of controls	No. of cases	OR	95% CI
All cancers										
0–5‡	2,086	1,328	2,111	1,370	0.95	0.84–1.08	426	264	0.89	0.72–1.09
0–20§	2,348	1,649	2,346	1,658	0.92	0.81–1.03	478	322	0.90	0.74–1.09
≥20‖	1,092	875	1,108	859	0.93	0.75–1.15	212	181	0.94	0.69–1.28
All¶	2,666	1,851	2,598	1,921	0.97	0.86–1.09	513	390	0.94	0.78–1.12
All leukemia										
0–5	191	45	173	47	1.01	0.55–1.86	33	8	1.06	0.40–2.80
0–20	222	50	173	53	1.66	0.90–3.05	38	11	1.54	0.64–3.72
≥20	109	25	100	28	0.87	0.32–2.38	17	5	1.01	0.26–3.96
All	252	60	206	61	1.40	0.77–2.54	36	10	1.44	0.59–3.49
Chronic lymphoid leukemia										
0–5	46	10	33	10	4.06	0.74–22.38	8	2	3.25	0.37–28.61
0–20	65	13	49	16	4.07	0.92–18.02	14	5	4.03	0.76–21.35
≥20	44	11	45	12	0.62	0.09–4.45	7	3	0.73	0.06–8.33
All	67	17	80	22	1.36	0.41–4.46	17	4	1.74	0.38–7.89
Acute nonlymphoid leukemia										
0–5	88	22	85	21	0.70	0.29–1.66	21	5	0.78	0.21–2.95
0–20	103	22	76	27	1.93	0.82–4.56	22	5	1.14	0.32–4.10
≥20	40	8	36	11	1.24	0.25–6.14	7	2		
All	116	27	82	27	1.58	0.67–3.72	16	5	1.53	0.42–5.64
Acute myeloid leukemia										
0–5	76	18	70	20	0.83	0.32–2.14	18	4	0.63	0.14–2.96
0–20	85	19	65	22	1.56	0.59–4.15	19	3	0.63	0.12–3.19
≥20	26	5	24	7	4.57	0.22–93.51	4	1		
All	97	22	61	21	2.08	0.75–5.71	12	3	2.07	0.39–11.01
Malignant brain cancer										
0–5	158	37	150	42	1.18	0.63–2.21	38	9	0.81	0.30–2.21
0–20	165	35	135	43	1.87	0.93–3.75	34	10	1.78	0.69–4.62
≥20	46	9	58	14	1.05	0.20–5.38	12	5	5.90	0.37–94.41
All	176	38	143	44	1.95	0.98–3.86	32	12	2.14	0.80–5.72
Astrocytoma										
0–5	67	17	57	14	1.19	0.44–3.20	17	2	0.54	0.10–2.94
0–20	61	12	44	11	3.99	0.72–22.03	13	5	11.10	1.44–85.63
≥20	13	2	14	5			3	1		
All	61	12	44	11	3.69	0.61–22.20	11	5	28.48	1.76–461.3
Glioblastoma										
0–5	57	12	53	15	1.01	0.34–3.05	12	3	0.50	0.08–3.30
0–20	59	13	62	19	1.35	0.50–3.60	11	3	1.01	0.22–4.69
≥20	14	5	27	3			4	1		
All	61	16	60	16	0.98	0.36–2.67	11	3	0.63	0.13–2.97

(*Table 5 continues next page.*)

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TABLE 5. Continued

Cancer site and time of exposure to magnetic fields (years) relative to diagnosis	Exposure group									
	<Median		≥Median				≥90th percentile			
	No. of controls	No. of cases	No. of controls	No. of cases	OR	95% CI†	No. of controls	No. of cases	OR	95% CI
Melanoma										
0–5	108	34	191	42	0.63	0.32–1.22	41	9	0.55	0.20–1.46
0–20	112	41	195	40	0.49	0.26–0.94	33	9	0.75	0.27–2.07
≥20	46	17	57	12	1.49	0.40–5.58	12	2	1.76	0.22–14.05
All	135	44	193	42	0.65	0.35–1.22	34	8	0.89	0.32–2.44

* The odds ratios (OR) compare the indicated groups of participants with the baseline group (exposure less than the median) and are adjusted for socioeconomic status.

† CI, confidence interval.

‡ 0–5, exposure in the 5 years immediately preceding diagnosis, analysis restricted to subjects employed at least 4 years of this period (median = 0.7 microtesla (μT)-years; 90th percentile = 2.6 μT-years).

§ 0–20, exposure in the 20 years immediately preceding diagnosis; analysis restricted to subjects employed at least 10 years of this period (median = 2.5 μT-years; 90th percentile = 10.3 μT-years).

‖ ≥20, exposure 20 years or more before diagnosis; analysis restricted to subjects employed at least 10 years of this period (median = 2 9 μT-years; 90th percentile = 18.0 μT-years).

¶ All, all exposure, restricted to subjects employed at least 10 years of this time (median = 3.5 μT-years; 90th percentile = 17.9 μT-years).

sults, is highly dependent on the specific adjustment for SES. For acute nonlymphoid leukemia, the odds ratio remains essentially the same from the second to the fourth group. For acute myeloid leukemia, the odds ratio dropped from a peak of 4 in the second group to about 2 in the upper two groups.

Table 7 shows odds ratios by mean exposure to magnetic fields, restricting analysis to men who had been working at least 10 years. To aid direct comparison with previous studies, we compared participants exposed to levels greater than 0.2 μT with those exposed to levels less than 0.2 μT, and those exposed to levels greater than 0.3 μT with those exposed to levels less than 0.3 μT. The odds ratios for acute nonlymphoid and acute myeloid leukemia were particularly elevated in men exposed to levels greater than 0.2 μT. As with the results for leukemia in general, this was not consistent between utilities.

The variation across utilities in the odds ratios for leukemia noted above in our comments on table 4 was present also for most of the analyses reported in tables 5–7. In general, the pattern was of an association in OH, a weaker one in EDF, and no association in HQ. Given this lack of consistency, the combined odds ratios should be interpreted cautiously.

DISCUSSION

Leukemia

Our observation of an elevated risk for acute nonlymphoid leukemia (and its major component, acute myeloid leukemia) among workers exposed to levels above the median and those exposed to levels higher than a mean of 0.2 μT seems to support the hypothesis of an association with magnetic fields. However, the detailed analyses carried out do not yield a consistent picture of a causal association. There were no dose-response trends with increasing exposure. Actually, the risks were similarly increased in all percentile categories above the baseline. The risk was weaker in the >0.3 μT exposure category than in the >0.2 μT exposure category, and the association was not homogeneous across the three utilities. Therefore, caution must be exercised in interpreting the present results as evidence of a causal association.

Recently, two major studies involving extensive measurements of magnetic fields have been published, one on a cohort of electric utility workers (8) and one on workers from the general population (7). The first yielded completely negative results; in the second an association was observed be-

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TABLE 6. Adjusted odds ratios* and exposure-response relation for selected cancers among electric utility workers in Ontario and Quebec, Canada, and France, by cumulative exposure group: 1970–1989

Cancer site and cumulative exposure group†	No. of controls	No. of cases	OR	95% CI‡	OR for trend§	95% CI
All cancers						
Group 1	3,135	1,993	1			
Group 2	1,497	1,068	1.01	0.90–1.14		
Group 3	892	647	1.00	0.87–1.16		
Group 4	582	443	1.01	0.86–1.20	1.01	0.86–1.18
All leukemia						
Group 1	307	70	1			
Group 2	118	29	1.33	0.73–2.43		
Group 3	80	28	1.92	0.97–3.78		
Group 4	41	13	1.75	0.77–3.96	1.45	0.68–3.08
Chronic lymphoid leukemia						
Group 1	68	17	1			
Group 2	39	8	1.11	0.31–3.92		
Group 3	28	10	2.18	0.58–8.27		
Group 4	21	6	1.71	0.44–6.66	1.35	0.44–4.14
Acute nonlymphoid leukemia						
Group 1	140	27	1			
Group 2	45	15	2.44	0.99–5.99		
Group 3	36	12	2.28	0.82–6.36		
Group 4	17	6	2.52	0.70–9.09	1.68	0.51–5.51
Acute myeloid leukemia						
Group 1	112	21	1			
Group 2	33	13	4.05	1.38–11.95		
Group 3	28	9	2.21	0.67–7.33		
Group 4	13	4	2.68	0.50–14.50	1.53	0.31–7.62
Malignant brain cancer						
Group 1	250	60	1			
Group 2	67	23	1.69	0.85–3.33		
Group 3	62	13	1 13	0.50–2.56		
Group 4	36	12	1.95	0.76–5.00	1.67	0.68–4.11
Astrocytoma						
Group 1	107	29	1			
Group 2	22	6	0.79	0.20–3.01		
Group 3	18	1	0.19	0.02–1.89		
Group 4	13	5	12.29	1.05–143.5	9.41	1.07–82.79
Glioblastoma						
Group 1	71	17	1			
Group 2	26	10	1.82	0.57–5.75		
Group 3	26	5	0.89	0.21–3.77		
Group 4	13	3	0.81	0.17–3.91	0.68	0.15–2.99
Melanoma						
Group 1	175	52	1			
Group 2	123	30	0.84	0.47–1.51		
Group 3	65	14	0.80	0.35–1.80		
Group 4	38	10	1.03	0.41–2.58	1.14	0.47–2.74

* The odds ratios (OR) are adjusted for socioeconomic status.

† Group 1, <median (0–3.09 microtesla (μT)-years); group 2, median–75th percentile (3.1–6.89 μT-years); group 3, 75th–90th percentiles (6.9–15.69 μT-years); group 4, ≥90th percentile (≥15.7 μT-years).

‡ CI, confidence interval.

§ The estimated odds ratio for the fourth group versus the first, on fitting a linear term to a logistic model.

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TABLE 7. Adjusted odds ratios* for selected cancers among electric utility workers† in Ontario and Quebec, Canada, and France, by mean exposure to magnetic fields: 1970–1989

Cancer sites of a priori interest	Exposure group									
	<0.2 μT		≥0.2 μT			<0.3 μT		≥0.3 μT		
	No. of controls	No. of cases	No. of controls	No. of cases	OR	95% CI‡	No. of controls	No. of cases	No. of controls	No. of cases	OR	95% CI
All cancers	3,435	2,418	1,829	1,354	0.96	0.86–1.08	3,979	2,823	1,285	949	0.98	0.87–1.10
All leukemia	318	71	140	50	1.61	0.93–2.81	367	92	91	29	1.14	0.66–1.97
Chronic lymphoid	94	22	53	17	1.40	0.52–3.77	108	29	39	10	0.89	0.35–2.29
Acute nonlymphoid	138	28	60	26	2.36	1.00–5.58	158	37	40	17	1.77	0.80–3.92
Acute myeloid	111	23	47	20	2.25	0.79–6.46	127	30	31	13	1.91	0.70–5.18
Malignant brain	204	46	115	36	1.64	0.85–3.16	235	55	84	27	1.51	0.80–2.83
Astrocytoma	68	13	37	10	4.28	0.64–28.52	73	16	32	7	1.31	0.30–5.68
Glioblastoma	75	20	46	12	0.90	0.33–2.44	92	24	29	8	0.92	0.33–2.51
Melanoma	181	53	147	33	0.96	0.50–1.85	231	62	97	24	1.21	0.64–2.29

* The odds ratios (OR) compare the indicated group of participants with the baseline group (<0.2 microteslas (μT) and <0.3 μT, respectively), and are adjusted for socioeconomic status.
† This analysis was restricted to men who had been employed at the utility for 10 years or more.
‡ CI, confidence interval.

tween magnetic fields and chronic lymphoid leukemia but not acute myeloid leukemia.

Although not completely consistent, our results are compatible with the results of these two previous studies. In comparison with the former, we have followed a different design: Sahl et al. (8) analyzed mortality, assessing exposure in relation to time of death and limiting analysis to all leukemia. We studied incident cases, assessed exposure in relation to time of diagnosis, and scrutinized each type of leukemia. Had we limited our analysis to all leukemia, we would have observed a somewhat elevated but not statistically significant odds ratio for the group with exposure above the median level (3.1 μT-years) (odds ratio (OR) = 1.54, 95 percent CI 0.90–2.63), and, therefore, our conclusions would have been similar to those of Sahl et al.

Contrary to Floderus et al. (7), we found no clear association between exposure to electromagnetic fields and chronic lymphoid leukemia. Here again, the apparent contradiction can be somewhat explained by the difference between the two studies. The proportion of chronic lymphoid leukemia among all leukemia was much lower in our study than in that of Floderus et al.: 41 of 140 (29 percent) versus 112 of 250 (45 percent), respectively. This was inherent in the structural design of our collaborative cohort (the EDF cohort did not include cases older than 60 years), and diminished our ability to observe an association with chronic lymphoid leukemia if it did exist. When looking at the OH and HQ sectorial results, we found that the trends seemed to support an age factor. The OH cohort, which had the oldest participants (mean age at diagnosis = 62.6 years) yielded a nonstatistically significant trend for chronic lymphoid leukemia with increasing exposure (≤4.9 μT-years, OR = 1.0; 4.9–9.1 μT-years, OR = 1.72, 95 percent CI 0.37–8.09; 9.1–27.2 μT-years, OR = 2.67, 95 percent CI 0.53–13.51; and >27.2 μT-years, OR = 3.34, 95 percent CI 0.35–31.90). However, the HQ cohort (mean age at diagnosis = 57.1 years), which also followed up its members to their deaths,

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did not yield any indication of an increased risk for chronic lymphoid leukemia with increasing exposure to magnetic fields (≤6.1 μT-years, OR = 1.0; 6.1–11.8 μT-years, OR = 0.76, 95 percent CI 0.13–4.31; 11.8–23.6 μT-years, OR = 2.69, 95 percent CI 0.47–15.35; and >23.6 μT-years, 0 cases, 3 controls).

For cumulative exposure to magnetic fields in the 5 years preceding diagnosis and the 20 years preceding diagnosis (our analysis closest to that of Floderus et al. (7)), the odds ratios for chronic lymphoid leukemia for exposure above the median were 4.06 and 4.07, respectively (table 5)—quite close to conventional levels of statistical significance ($p = 0.11$ and 0.06, respectively).

As for our observation of an association between exposure and acute myeloid leukemia, the studies reported to date in the literature have yielded conflicting results, some showing the presence of such an association (22–28), others observing no such association (7, 29, 30), and some yielding results that are difficult to interpret (31–35).

Brain cancers

An association between brain cancer and exposure to electromagnetic fields has also been reported in the literature (6). This was more so in earlier studies, most recent studies having yielded limited evidence (7) or completely negative results (8, 28, 36). We did observe an excess risk for astrocytoma among workers in the 90th percentile of magnetic field exposure and above, but this association was based on small numbers of cases and greatly diminished when an exact method was used in the statistical analysis. The great dependence of this observation on the statistical analysis leads us to believe that the noted association is more likely artificial than real.

Skin melanoma

In the literature, excess risk for skin melanoma has been reported among electric engineers and workers in the electronics industry (37–40). This prompted our study to consider skin melanoma as an a priori tumor for which an association with electromagnetic fields should be explored. Our results are essentially negative. No associations between skin melanoma and exposure to magnetic fields were found. The upper confidence intervals of the odds ratios in table 3 show that this study can with 95 percent confidence exclude odds ratios higher than 1.48 for moderate (above median) exposures and 2.58 for high (above 90th percentile) exposures.

Hormone-sensitive cancers

Following the observation that electromagnetic fields decrease the level of circulating melatonin in exposed animals and humans, Stevens (41) proposed that the mechanism by which electromagnetic fields increase cancer risk is through increasing circulating estrogen and prolactin (41). Observations on male breast cancer among electric workers by Matanoski et al. (42), Demers et al. (43), and Tynes and Andersen (44) have given support to Stevens' theory. In the present study, we have observed seven cases of breast cancer: one at HQ, three at OH, and three at EDF. The numbers were too small for an analysis as formal as was possible for other cancer sites. However, a simple tabulation revealed no difference in exposure between breast cancer cases and controls. We also calculated, using a proportional incidence analysis based on age-adjusted incidence ratios specific to each province or country, that we would normally have expected 8.25 such cancers in our cohort (HQ, 1.50; OH, 2.86; EDF, 3.89). Therefore, no excess of male breast cancer is apparent.

Similarly, one may address the hypothesis of an association between prostate cancer and electromagnetic fields. In our study, there were 357 prostate cancers. Analysis of prostate cancers did not show any increase in risk with increasing exposure to magnetic fields.

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Methodological considerations

Exposure measurement error (misclassification). Despite the large number of exposure measurements made for this study, there remained much imprecision in assessing exposure, and therefore, misclassification bias certainly occurred. Probable misclassification is hard to quantify. The precision with which mean magnetic field exposures were estimated is shown by the confidence intervals in table 1. The precision of the means for the OH cohort, for which confidence intervals are not given, is probably broadly similar. There is clearly uncertainty regarding the mean exposure in several jobs; nonetheless, broad patterns of exposure were established beyond reasonable doubt.

Apart from arising from errors in estimating means, misclassification of individuals will also arise from the variation in exposure levels between workers in the same row of the job exposure matrix (table 1). Although the means for job categories differed substantially (and statistically significantly) in all three utilities, much variation remained within job categories. Specifically, job category (job exposure matrix row) explained 49.6 percent, 42.1 percent, and 30.9 percent of the variance in the logarithms of weekly mean magnetic fields in HQ, OH, and EDF, respectively.

If the true risk factor was not the mean or cumulative exposure (say peak or intermittent exposures), our estimated exposures should be considered as surrogates for the true metric, and to the extent that the surrogate is not closely correlated with the true metric, additional effective misclassification will have resulted. Many metrics (peaks, time above proposed thresholds), however, were shown in a pilot study to be quite closely correlated in utility workers with the mean of a week's measurements (45). Additional analyses using indices based on geometric means (shown in table 1) gave broadly similar results.

The omission of information on exposure to magnetic fields outside work at the utility (e.g., at home or in hobby activities) will also have introduced misclassification of participants' exposure if, as seems reasonable, total exposure from all sources was the true risk factor. Note that if exposure outside the utility were the same for all participants, this would simply add a constant to all exposures and not affect division into groups. It is only variation in extra-utility exposure between participants that would cause misclassification.

There is no reason to suppose that errors in estimating exposures are any different for cases than for controls, so that misclassification is, in this sense, nondifferential. Thus, its main effect will have been to bias truly nonnull odds ratios toward one and to diminish the power of the study to find associations with magnetic fields if any are present. Misclassification may, however, have distorted the shape of the dose-response relation (46, 47).

Confounding bias. Our principal method of controlling for confounding by nonoccupational risk factors has been through an indication of socioeconomic status. The plausibility of other nonoccupational factors leading to confounding bias varies by cancer site. Information on exposure to other occupational risk factors for cancer varied in type and quality among utilities. An exception was ionizing radiation, on which good quality data were available for all utilities. However, the surveys of other occupational exposures revealed few exposures present in sufficient quantities to be plausible confounders. A few were substantial enough for associations with risk to be observed, but adjusting for these in the analysis of magnetic fields changed the odds ratios very little.

The number of years of employment at the utility was considered as a possible confounder in certain analyses. This was mainly because short-term employees have sometimes been shown to be unrepresentative with respect to cancer risk factors (48), but also to allow for a confounding effect of exposure to magnetic fields before and after employment at the utility. Because the number of years outside the utility is inversely

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proportional to the number of years of employment at the utility (after matching by age), entering this variable in the logistic regression has the effect of allowing for an effect of such exposure.

Information on smoking was available for participants in one utility only (HQ), and our ability to control directly for confounding by smoking was therefore limited. However, the data from HQ and other information argue against appreciable confounding by smoking. At HQ, smoking was not associated with exposure to magnetic fields after stratification by SES, nor did odds ratios for lung cancer by cumulative exposure to magnetic fields change appreciably after adjustment for smoking in addition to SES. As the association of smoking with the causes of a priori interest is much weaker than its association with lung cancer, appreciable confounding appears very unlikely. A cross-sectional study of current EDF workers also showed minimal association between smoking and exposure to electromagnetic fields (49). These specific data complement a considerable body of general information that suggests that even for cancer sites for which smoking is a strong risk factor, differences in smoking between groups of workers are usually insufficient to cause appreciable confounding (50).

Combining results across utilities. This was a multicenter study in which data were collected independently at the three participating utilities according to a common protocol. Despite the common protocol, the three component studies differed in some important respects:

1. The underlying cohorts were composed differently, the principal differences being the ending of follow-up at EDF at termination of employment and the inclusion at OH of workers who had retired but were alive in 1970.
2. The background cancer rates and prevalent risk factors may have differed between countries or provinces, in particular in France (e.g., elevated rates of cancer of the lip, buccal cavity, and pharynx).
3. The distribution of estimated exposures differed across the utilities, with EDF having a much smaller proportion of participants in the groups with higher exposure to magnetic fields than HQ or OH. (Further investigation of the differences in exposure estimates among the utilities allowed us to conclude that the different estimates probably reflect differences in actual exposure rather than measurement errors.)
4. The method used at OH to arrive at a job exposure matrix was slightly different from that used at EDF and HQ.

These differences do not preclude the pooling of data from all three utilities, but do necessitate special caution in interpretation. We have been careful to check routinely whether the odds ratios by magnetic fields exposure category were compatible across the three utilities, using tests for utility–exposure interactions (effect modification). Where these tests provided evidence for variation in the odds ratios across utilities (e.g., for leukemia), we noted the inconsistency of results and focused more attention on the results specific to the utility or utilities in which the association was observed.

Even in the absence of statistically significant utility–exposure interactions, the differences between utilities affected the interpretation. In particular, the generally lower exposures to magnetic fields at EDF than at HQ or OH led to very few EDF participants being represented in the high exposure categories, so that the combined elevated risks in the high exposure categories are effectively for OH and HQ. Conversely, so few HQ participants are represented in the low exposure categories that the HQ results for rarer cancers are rather imprecise. Odds ratios were also calculated by using groups defined by dividing each utility separately at the 50th, 75th, and 90th percentiles pertaining to that utility. In general, and for leukemia in particular, these analyses yielded broadly similar results.

If there is a long-term effect, one would expect that the observed association would

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be decreased at EDF, given that cases occurring after retirement were not included. This loss of power is particularly important, since workers who had the most exposure retire earlier, and cases occurring among these workers after the age of 60 years could not be included in the study.

CONCLUSION

Despite the attempts made in this study to achieve adequate power, definitive evidence of an association between exposure to magnetic fields and leukemia and brain cancer has not been obtained. One of the main hypotheses tested was the association between magnetic fields and acute nonlymphoid leukemia (acute myeloid leukemia) that has been reported in several other studies. Considering that among all the cancers analyzed in our study, this is the one for which a statistically significant association was found, we believe our results speak for an association between occupational exposure to magnetic fields and at least one type of leukemia. It remains possible that our observation was due to chance, but it is more likely that the inconsistencies in our results correspond to the as yet underestimated difficulty of arriving at an accurate exposure estimate for each study participant. The absence of a clear association of magnetic field exposure with chronic lymphoid leukemia, which seems to contradict the results of previous studies, may have been the result of limited follow-up beyond the age of 60 years, and therefore may not be indicative of a true absence of such an association.

Our observation of an elevated risk for astrocytoma among men exposed to levels at or above the 90th percentile, given similar reports in the literature, remains suspicious. However, the evidence brought by this study is much less convincing, since it is based on only five cases and depends on the use of one type of statistical analysis. Our study did not observe an association between magnetic fields and male breast cancer, skin melanoma, or prostate cancer.

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