Scand J Work Environ Health 1996;22(6):415-424

<https://doi.org/10.5271/sjweh.162>

Issue date: Dec 1996

Exposure to 60-Hz magnetic and electric fields at a Canadian electric utility

by [Deadman J--E](#), [Armstrong BG](#), [Thériault G](#)

Key terms: [correlation](#); [exposure index](#); [job-exposure matrix](#); [positron exposure meter](#); [sampling strategy](#); [variability](#)

This article in PubMed: www.ncbi.nlm.nih.gov/pubmed/9000308

This work is licensed under a [Creative Commons Attribution 4.0 International License](https://creativecommons.org/licenses/by/4.0/).

Exposure to 60-Hz magnetic and electric fields at a Canadian electric utility

by Jan-Erik Deadman, MSc,¹ Benedict G Armstrong, PhD,^{1,2} Gilles Thériault, PhD¹

Deadman J-E, Armstrong BG, Thériault G. Exposure to 60-Hz magnetic and electric fields at a Canadian electric utility. *Scand J Work Environ Health* 1996;22:415–24.

Objectives The purpose of this study was to estimate exposure to extremely low frequency (ELF) magnetic and electric fields in the Québec electrical utility Hydro-Québec.

Methods Personal exposures to ELF magnetic and electric fields were measured for workers randomly selected from 32 job categories at Hydro-Québec. Weekly arithmetic and geometric means, and other indices of exposure were estimated from 465 worker-weeks of data.

Results By job category, the arithmetic means of the ELF magnetic field exposures ranged from 0.09 to 2.36 μT . Those of the ELF electric field exposures ranged from 2.5 to 400 $\text{V} \cdot \text{m}^{-1}$. Within each field, correlations of either the arithmetic or geometric means with alternative indices, including an index of the time rate of change, were generally high ($r \geq 0.8$). Exceptions were the 20th percentile of the electric means and the proportion of time above 12.4 and 100 μT . The day-to-day variation of exposure was greater than the variation between workers. The median between-day and between-worker components of variance (as geometric standard deviations) by job category were 2.13 and 1.71 for magnetic fields (2.24 and 1.81 for electric fields).

Conclusions Substation workers, hydroelectric generating station operators, and cable splicers showed the highest arithmetic means for 60-Hz magnetic fields above 1 μT . For 60-Hz electric fields, forestry workers, equipment electricians in 735 kV substations, and distribution linemen (contact method) had arithmetic mean exposures greater than 100 $\text{W} \cdot \text{m}^{-1}$. Of the total variance in the logarithms of the weekly magnetic and electric field means, job category explained 49.6% and 59.5%, respectively.

Key terms correlation, exposure indices, job-exposure matrix, Positron exposure meter, sampling strategy, variability.

The assessment of exposure to extremely low-frequency (ELF) electric and magnetic fields has evolved substantially since job titles were first used as exposure surrogates. Advances in measurement technology allow personal exposure to be monitored in substantial detail over one or more workshifts (1). While a variety of exposure indices can be calculated from these detailed measurements, little is known about their biological relevance. A reduced set of indices is thus desirable to avoid problems of interpretation when the associations of several candidate indices and health are examined on an equal basis. Furthermore, knowledge of the variability of exposures between workers and over time is essential to increasing the validity of exposure assessments and planning control measures. Several surveys using area and source measurements or personal monitoring have been conducted in the past to assess exposures to power-frequency electric and magnetic fields in electric utilities and other occupational environments and they have been re-

viewed elsewhere (2–3). In an earlier paper, (4) we summarized workers' ELF field exposures by their arithmetic and geometric means, as the values correlated well with many other indices of occupational exposure. More recently, two large-scale measurement campaigns based on personal monitoring have been carried out in the electric utility industry in the United States (5–6) for epidemiologic studies of ELF fields and cancer. The study of magnetic field exposures at Southern California Edison (SCE) by Sahl et al (5), using a data-logging meter, confirmed the high correlation of either the arithmetic or geometric means with alternative indices at the job title level, with some indication that the fractions of measurements exceeding 0.5 and 1.0 μT might also be useful in discriminating between occupational groups. In the study of five electrical utilities in the United States by Savitz et al (7), a time-averaging meter was used to estimate the arithmetic and geometric means of daily arithmetic mean magnetic fields for workers chosen ran-

¹ Department of Occupational Health, Faculty of Medicine, McGill University, Montreal (QC), Canada H3A 1A3.

² Current address: Environmental Epidemiology Unit, London School of Hygiene and Tropical Medicine, London, United Kingdom.

domly from 28 job groups. This study also found high correlations between either the arithmetic or geometric means and several alternative indices at the job-category level, for both magnetic and electric fields.

To provide exposure estimates for subjects of the Québec portion of the Canada-France study of extremely low-frequency electric and magnetic fields and cancer among electrical utility workers (8), we conducted an extensive survey of personal exposure to 60-Hz magnetic and electric fields among craft and office occupations at Hydro-Québec, a utility that produces, transports, and distributes electricity. The primary objective was to produce a representative job-exposure matrix for subjects of the cancer study covering the years 1945 to 1988. The survey was designed to improve on previous work by measuring personal exposures minute-by-minute over a full work week in a large group of workers selected randomly from 32 job categories over a two-year period. Our primary focus was on estimating arithmetic and geometric mean exposures, but we also wished to examine correlations of several alternative indices and describe the variation in exposure for individual workers (between days) and between workers. This report presents the results of the exposure survey and the analyses of correlation and variability. In 14 of the job categories, past exposure was judged to have differed sufficiently from the present to justify separate estimation. Therefore, we developed a task-based approach to correct current exposure estimates; it will be reported in a subsequent paper.

Methods

Grouping of jobs for the job-exposure matrix

An industrial hygienist and an occupational physician at the utility classified all the job titles ($N = 2466$) into two groups: an expected low-exposure group in which duration of daily proximity to energized equipment was estimated as less than 15 min (2300 jobs) and a second group expected to be exposed at levels higher than the expected low-exposure group (166 jobs). The two groups of job titles were then reviewed with the utility's joint health and safety committee to identify those with similar tasks which could be collapsed into single job categories. The 2300 jobs with expected low exposure were subdivided into blue-collar and white-collar categories, and the 166 jobs with expected high exposure were grouped into 30 job categories (tables 1 and 2).

Sampling strategy

The goal of the epidemiologic study (8) was to determine whether occupational exposures were associated with cancer. A pilot study had indicated that workers'

collaboration in wearing exposure monitors would be maximized if measurements were limited to the workplace (9). Thus we did not require participants to wear meters while away from work, but gave them the choice. Early in the study, we undertook a comparison of occupational and nonoccupational exposures of workers who had volunteered to wear the meter at home as well as at work. Results from a sample of 70 such workers, from job titles with the lowest and highest occupational magnetic field exposures (arithmetic means), showed correlations (r) of arithmetic mean exposures during work and during sleep of $r = 0.07$ for magnetic fields and $r = 0.06$ for electric fields. In the comparison of occupational and nonoccupational activities other than sleep, the correlations were $r = 0.03$ for magnetic fields and $r = 0.17$ for electric fields (10).

The measurement campaign covered nine of the ten administrative regions of the utility, and extended over three summer and three winter periods. The names of a total of 623 potential participants were selected at random from lists of permanently employed workers stratified by administrative region. These, and extra names for replacement of absences or refusals, were sent to management and union health and safety representatives in each region, who handled the contact, follow-up, and replacements of workers. In three regions, we gave utility representatives the option of randomly choosing work teams of three to five workers instead of individual persons. This option was offered at the request of the utility, to prevent the organizational difficulties that selection of individual workers from teams in different geographic locations would have caused. The option of sampling teams was offered for 10% of the sampled workers. The proportion actually sampled this way (less than 10%) is not easily ascertained.

Our initial objective, based on the magnitude of the within- and between-person variation found in a pilot study, was to measure occupational exposures over 5 d for between 10 and 20 workers for each of the 32 job categories. Sample sizes were weighted informally before the measurement campaign to reflect the size of the job group and the expected intensity and variability of exposures, and they were revised during the campaign according to measured intensity. In nine of the categories, fewer than 10 workers were measured. Five job categories had arithmetic means for the magnetic fields with an upper 95% confidence interval of less than 1.0 μT when samples of five or six workers were used, and the sampling was truncated for these categories. Two categories did not appear among the case and reference jobs (forestry workers, tree trimmers), and the sampling was also suspended for them. Time constraints prevented reaching the minimum requirement for two categories: hydroelectric generation foremen and licensed electricians.

Table 1. Occupational exposures to 60-Hz magnetic fields by job category at Hydro-Québec. [N = number of worker-weeks measured, AM_{am} = arithmetic mean of weekly arithmetic means, GM_{gm} = geometric mean of weekly geometric means, S_g = geometric standard deviation of the weekly means (crude between-worker), $_{ww}S$ = within-worker, minute to minute standard deviation (surrogate for $dB \cdot dt^{-1}$), $_{bw}S_g$ = geometric standard deviation, between-workers (by variance components), $_{ww}S_g$ = geometric standard deviation, within-workers (by variance components), RCC = regional control center, DCC = distribution control center]

Job category	N	Arithmetic mean			Geometric mean				
		AM _{am} (μ T)	95% CI	S _g	GM _{gm} (μ T)	Min · week ^{-1a}		bwS _g	wwS _g
						>12.4 μ T	>100 μ T		
Expected low-exposure jobs									
Blue-collar jobs ^b	15	0.15	0.10—0.31	2.39	0.03	2.9	0.2	1.80	1.88
White-collar jobs ^c	24	0.16	0.11—0.23	2.17	0.06	1.4	—	1.69	1.86
Hydroelectric generation									
Equipment electricians	20	0.99	0.68—1.98	2.53	0.23	19.5	1.1	2.24	2.02
Equipment mechanics	24	0.77	0.45—1.19	2.54	0.18	20.1	0.2	2.55	2.10
Foreman, operations and others	9	0.50	0.27—1.83	2.56	0.07	10.7	1.6	1.60	2.84
Operator, hydro generating station	11	1.56	0.94—4.13	2.40	0.67	13.8	0.8	2.33	1.55
Nuclear generation									
Equipment electricians	6	0.19	0.12—0.40	1.64	0.05	1.2	—	1.23	2.03
Operator, nuclear station	17	0.13	0.11—0.15	1.35	0.05	0.3	—	1.14	1.77
Diesel generation									
Operator, autonomous network	11	0.32	0.26—0.42	1.42	0.12	1.1	—	1.07	2.45
Transmission									
Forestry worker	5	0.22	0.20—0.25	1.10	0.10	—	—	1.00	1.83
Transmission splicer	12	1.79	1.13—4.09	2.29	0.24	41.4	5.3	1.85	2.51
Transmission lineman $\leq$ 735 kV	18	0.60	0.44—0.90	1.90	0.08	14.9	0.2	1.42	3.00
Substation									
Equipment electrician $\leq$ 735 kV	29	2.36	1.12—3.74	3.25	0.24	77.2	2.1	2.84	2.56
Equipment electrician 735 kV substation	22	1.78	1.45—2.30	1.62	0.54	16.2	0.1	1.51	1.76
Maintenance worker, civil and mechanical engineering	23	1.05	0.46—2.97	4.20	0.09	25.5	3.0	3.03	2.33
Operator, mobile	16	1.17	0.76—2.44	2.44	0.23	12.9	0.4	2.32	2.15
Operator, 735 kV substation	12	1.78	1.00—4.44	2.52	0.76	8.5	—	1.94	2.15
Technician, automatic control or relay	18	1.60	0.89—6.10	3.77	0.21	38.0	1.3	3.14	2.33
Distribution									
Emergency man	8	0.50	0.22—2.12	2.67	0.08	12.7	1.6	1.00	3.08
Foreman, OH lines	5	0.16	0.11—0.27	1.39	0.09	—	—	1.35	1.22
Foreman, UG lines	6	0.14	0.10—0.20	1.36	0.06	1.5	—	1.00	1.99
Lineman, contact and hotstick method	39	0.37	0.26—0.50	2.37	0.06	9.8	0.5	1.55	2.28
Lineman, contact method	23	0.83	0.60—1.50	2.41	0.13	31.7	—	2.16	2.30
Meter installer	10	0.42	0.23—1.19	2.44	0.08	14.8	0.1	1.89	2.08
Meter reader	14	0.17	0.13—0.24	1.64	0.05	1.6	—	1.43	1.84
Splicer, distribution	18	1.87	1.17—5.44	3.13	0.12	84.7	2.3	1.93	4.26
Tree trimmer	4	0.34	0.15—5.41	2.13	0.05	14.8	—	1.00	2.75
Others									
Estimator	10	0.13	0.10—0.18	1.45	0.06	—	—	1.25	1.65
Instructor	6	0.17	0.09—0.53	1.99	0.06	0.4	—	2.01	1.55
Licensed electricians	9	0.87	0.46—3.35	2.63	0.19	14.5	3.3	2.26	2.61
Operator-dispatcher RCC or DCC	10	0.09	0.06—0.15	1.75	0.04	0.2	—	1.73	1.53
Technician telecommunications	11	0.44	0.24—0.82	2.16	0.11	3.4	—	1.67	2.39

465

465

^a On the assumption of a 40-h work week.

^b *Blue-collar jobs*: clerk, accounting/judicial/mail/stores/data entry; meter inspector, storekeeper; mechanic, vehicles and equipment; toolkeeper; technician, planning/management.

^c *White-collar jobs*: agent, division head, section head, shift supervisor; consultant, systems management/personnel; engineer; commercial representative.

Measurement of magnetic and electric fields

Positron personal exposure meters (model 378108) and prototype meters developed by Hydro-Quebec's research institute (IREQ) were used to measure the flux density (B) of the three orthogonal components of the 60-Hz magnetic field and the perturbed 60-Hz electric field (E) perpendicular to the body surface. The characteristics of this meter, which records readings in 16 logarithmically

scaled exposure categories or bins, have been described previously (1, 9). The primary calibration of magnetic field response, which involved determining the precise threshold field level for lower bin edges for the three orthogonal field directions, was carried out before and after the sampling program with a Helmholtz coil arrangement. No drift in meter response was detected. An error of up to 10% difference between the readings and the bin edge values was accepted. Primary calibration of

Table 2. Occupational exposures to 60-Hz electric fields by job category at Hydro-Québec. [N = number of worker-weeks measured, AM_{am} = arithmetic mean of weekly arithmetic means, GM_{gm} = geometric mean of weekly geometric means, S_g = geometric standard deviation of the weekly means (crude between-worker), $_{ww}S$ = within-worker, minute to minute standard deviation (surrogate for $dB \cdot dt^{-1}$), $_{bw}S_g$ = geometric standard deviation, between-workers (by variance components), $_{ww}S_g$ = geometric standard deviation, within-workers (by variance components), RCC = regional control center, DCC = distribution control center]

Job category	N	Arithmetic mean			Geometric mean			
		AM _{am} (V · m ⁻¹)	95% CI	S _g	GM _{gm} (V · m ⁻¹)	20th percentile (V · m ⁻¹)	BW S _g	WW S _g
Expected low-exposure jobs								
Blue-collar jobs ^a	15	5.0	3.8—7.6	1.76	1.3	0.5	1.55	1.57
White-collar jobs ^b	24	5.8	4.0—10.1	2.44	1.3	0.5	2.08	1.65
Hydroelectric generation								
Equipment electricians	20	18.2	8.2—33.2	3.07	1.6	0.4	2.63	2.24
Equipment mechanics	24	14.5	7.5—19.8	2.55	1.4	0.7	2.02	2.23
Foreman, operations and others	9	12.4	6.8—106.7	3.31	1.0	0.4	2.44	3.06
Operator, hydro generating station	11	6.3	3.9—15.9	2.32	1.4	0.6	2.00	1.87
Nuclear generation								
Equipment electricians	6	2.8	1.8—6.6	1.71	0.8	0.4	1.60	1.60
Operator, nuclear station	17	2.5	1.8—4.2	2.06	0.6	0.3	1.81	1.83
Diesel generation								
Operator, autonomous network	11	4.8	2.4—18.8	3.00	1.0	0.4	2.07	2.00
Transmission								
Forestry worker	5	399.7	125.9—>1K.0	3.30	10.2	3.3	2.86	5.73
Transmission splicer	12	15.8	10.8—27.8	1.92	1.3	0.5	1.75	2.25
Transmission lineman ≤ 735 kV	18	58.0	38.4—119.4	2.51	2.4	0.4	1.77	4.44
Substation								
Equipment electrician, ≤ 735 kV	29	52.1	35.8—158.9	3.90	1.8	0.6	3.01	3.10
Equipment electrician, 735 kV	22	122.4	78.1—268.5	2.91	3.6	1.1	2.55	2.96
Maintenance worker, civil or mechanical engineering	23	31.8	18.5—92.5	3.69	1.9	0.6	2.12	3.10
Operator, mobile	16	12.0	8.1—23.3	2.29	1.2	0.4	1.78	2.36
Operator, 735 kV substation	12	36.9	17.1—416.2	4.57	2.1	0.7	3.03	3.18
Technician, automatic control or relay	18	8.6	6.0—13.9	2.07	1.4	1.0	1.85	2.13
Distribution								
Emergency man	8	12.7	6.5—71.1	2.78	1.8	1.2	1.25	2.46
Foreman, OH lines	5	5.8	4.2—9.1	1.34	1.1	0.3	1.00	2.22
Foreman, UG lines	6	3.0	2.0—6.6	1.67	0.9	0.3	1.44	1.83
Lineman, contact or hotstick	39	83.2	62.0—141.4	2.76	2.4	0.5	1.81	4.34
Lineman, contact	23	127.1	85.9—283.7	2.88	2.3	0.5	1.48	4.84
Meter installer	10	5.5	4.4—7.3	1.40	1.5	0.6	1.28	1.50
Meter reader	14	10.0	7.6—15.7	1.78	2.5	0.8	1.82	1.70
Splicer, distribution	18	9.7	6.8—15.5	2.06	1.6	0.4	1.63	2.30
Tree trimmer	4	37.5	16.0>1000.0	2.34	3.4	0.6	1.00	2.94
Others								
Estimator	10	4.3	2.9—8.7	1.95	1.2	0.5	1.76	1.66
Instructor	6	2.8	1.8—7.0	1.75	1.0	0.4	1.53	1.86
Licensed electricians	9	12.5	6.1—49.0	2.72	1.1	0.4	1.80	3.10
Operator or dispatcher RCC or DCC	10	3.2	2.1—5.6	1.82	1.1	0.6	1.61	1.59
Technician, telecommunications	11	5.1	3.1—11.8	2.24	1.1	0.4	1.76	2.08
465								

^a Blue-collar jobs: clerk, accounting/judicial/mail/stores/data entry; meter inspector, storekeeper; mechanic, vehicles and equipment; toolkeeper; technician, planning/management.

^b White-collar jobs: agent, division head, section head, shift supervisor; consultant, systems management/personnel; engineer; commercial representative.

the electric field response was done using two parallel plates to generate a uniform field region of known magnitude (11). Before each use, meter timing and calibration were verified by exposing meters to a known magnetic field in a portable field generator and noting the time.

Data analysis

After exposure data were transferred to a computer, the software-displayed time of the calibration mark made by

the portable magnetic field generator was checked, and discrepancies of over 5 min were resolved by adjusting the start time on the data file. Time information recorded on the workers' activity diaries was checked for consistency with the displayed meter data. Work start and stop times were noted primarily from the diaries, but checked using the electric field display of the software as a guide. (Electric fields are easily perturbed by body motion, and the pattern of their record indicates whether the meter is stationary or moving.) When a day of measurement had

at least 6 h of magnetic and electric field data consistent with the activity diary, the day was considered valid. With the meter software, exposure data for each valid day were then summarized into a "histogram" file containing the number of measurements in each of the 16 bins for both fields. The mean duration of the measurements for all 465 workers was 5.7 d, as some workers wore meters for more than the five required days. There were 12 workers for whom 2 d of valid data were retained, and four for whom only 1 d was retained. Daily histogram files were summed by worker to produce a weekly histogram file. Weekly arithmetic means were then obtained for each worker by multiplying the week's total number of readings in each bin by the bin midpoint, summing the products, then dividing by the total number of readings for that worker. Geometric means for a week were calculated similarly, except that the logarithms of the midpoints of the bins were used and the antilog of the final result was taken. Out of 623 workers, we obtained collaboration from 563. Of these, data from 67 participants were lost because of meter failure in the field. Of the remaining 496 workers, 57 recordings were judged as suspicious or unrepresentative of usual work conditions for the job category. Suspicious recordings ($N = 21$) showed electric or magnetic fields that were chronologically incompatible with the activity diary, or unusual recordings indicative of meter malfunction. Unrepresentative work conditions ($N = 36$) involved temporary assignment to a job different from that intended or of work situations chosen by management to give interesting results. In all, 439 workers had one or more days of valid measurement.

From our pilot study (9), we added data from 17 workers in five exposed job categories and nine workers in the white-collar category. These workers had not been randomly chosen, but were selected by foremen as representative of their job. During a reexamination of the pilot study data, the originally reported magnetic (but not electric) field values were found to be higher than the values calculated for the current study from the same data, by a factor of barely over 2, on the average, with the ratios of old to new data for specific jobs ranging from 1.5 to 2.9. These differences were found to be due to an error in the early software used to display the mean field values recorded by prototype dosimeters (12).

As the focus of the epidemiologic study was on summary measures that represent time averages of field strength, arithmetic means of weekly arithmetic means, geometric means of weekly geometric means, and the 95% confidence intervals (95% CI) of these (13) were calculated for each job category. For this report, we also calculated the geometric means of the weekly arithmetic means, several "threshold" levels (proportions of time for each worker-week during which fields were in excess of the following levels: 20 and 78 $V \cdot m^{-1}$, and 0.2, 0.39,

0.78, 1.56, 6.25, 12.4 and 100 μT) and the 20th and 90th percentiles. Cut points were chosen to be as compatible as possible with other reports, but the bin boundaries of the meter imposed some constraints. The possibility that the biological effects of magnetic fields may be related to the time rate of change ($dB \cdot dt^{-1}$) (14) led Breyse et al (15) to measure the average difference between successive 1-min measurements. From our data, we devised a surrogate for $dB \cdot dt^{-1}$ by estimating the minute-to-minute standard deviations of the magnetic and electric fields for each individual worker.

All the indices were calculated first for each worker within a job category and then summarized by the arithmetic means across all workers within the category. The correlations of the indices were calculated at the job-category level, with the highly exposed category of forestry workers excluded from the electric field correlation analyses as they were not present in the case-referent study. We also estimated the variation in exposure between workers and between days (for individual workers) by a oneway analysis of variance of the logarithms of each worker's daily mean exposures, using a modified denominator to account for the unequal number of days the exposure meters were worn (16).

Results

The arithmetic and geometric means of the 60-Hz magnetic and electric fields are shown in tables 1 and 2 by job category. The geometric means shown are the geometric means of the workers' weekly *geometric* means, as reported in the cancer study (8). For clarity, indices correlated at $r \geq 0.8$ are not shown, with the exception of the day-to-day variation in electric fields [$_{ww}S_g$, expressed as geometric standard deviation (GSD)], for consistency with the table of magnetic field values. A complete set of results is available from the authors.

Magnetic fields

From table 1, magnetic field exposures were highest overall for the substation jobs, with the arithmetic mean exposures ranging from 1.05 μT for the maintenance workers to 2.36 μT for the equipment electricians in unstaffed substations of 735 kV or lower voltage. The equipment electricians' exposures resulted from the installation, maintenance, and servicing of electrical apparatus in substations, typically transformers, circuit breakers and disconnecting switches. Although the electricians usually worked on deenergized equipment, they were typically surrounded by live equipment and conductors. Hydroelectric generation jobs also had elevated exposures to magnetic fields, ranging from 0.5 μT for foremen to 1.56 μT for operators. The operators spent

30% of their time inspecting and operating generating units on the power-house alternator floor and carrying out inspection and switching operations in the power-house substation. The average exposure over these two locations was $2.5 \mu\text{T}$. The remainder of the operators' time was spent in the control room, at an average $1.1 \mu\text{T}$, performing functions such as monitoring the output of the generating units and operating remote-controlled devices. The exposures of equipment electricians in these stations ($0.99 \mu\text{T}$) were lower than the operators', as they spent less time near energized equipment. Equipment mechanics, who repaired, maintained, and installed mechanical components of power-house and substation equipment, spent less time close to energized equipment than the electricians, with correspondingly lower exposures ($0.77 \mu\text{T}$).

Within the other major facilities at the utility, magnetic field exposures showed considerable variability across job categories. The highest exposures were measured for trades working near energized conductors, the exposures generally depending on the number of conductors, their current capacity, and the time spent near them. For example, transmission and distribution cable splicers ($1.80, 1.87 \mu\text{T}$) install, maintain and repair underground cables, spending an average of $15 \text{ h} \cdot \text{week}^{-1}$ in underground cable vaults. While most cable splicers' work is done on deenergized cables, other cables in the vaults are usually live. The mean exposure for time in the distribution cable vaults was $4.77 \mu\text{T}$. When exposures were expressed as the mean duration of time above $100 \mu\text{T}$ for a 40-h workweek (correlated at $r = 0.55$ for the arithmetic means and $r = .09$ for the geometric means), 17 job categories showed exposure above this level. The trades with the highest weekly durations above $100 \mu\text{T}$ were splicers working on transmission cables ($5 \text{ min} \cdot \text{week}^{-1}$), substation maintenance workers, and licensed electricians ($3 \text{ min} \cdot \text{week}^{-1}$).

The measurements of the blue-collar and white-collar job categories confirmed expectations by showing low and similar magnetic fields (0.15 and $0.16 \mu\text{T}$). The magnetic field exposures were also low for several other groups, including nuclear generating station operators, estimators, and foremen for overhead and underground line workers.

Electric fields

From table 2 it can be seen that electric fields were highest for jobs involving prolonged and close exposure to unshielded conductors. Although from a small sample ($N = 5$) the highest mean exposures of $400 \text{ V} \cdot \text{m}^{-1}$ (95% CI $126\text{--}1000 \text{ V} \cdot \text{m}^{-1}$) were registered for the forestry workers (who did not contribute subjects to the case-referent study) who had spent about 30 h a week spraying herbicides under transmission lines. Although

transmission linemen worked closer to the conductors, they spent less time per week (mean 13 h), reflected in the lower mean electric field of $58 \text{ V} \cdot \text{m}^{-1}$. Other trades involving extended periods near live unshielded conductors are the two categories of substation equipment electricians ($122 \text{ V} \cdot \text{m}^{-1}$ and $52 \text{ V} \cdot \text{m}^{-1}$) and distribution linemen. As expected, the distribution linemen who handled live wires mainly by the insulated-glove (contact) method were more highly exposed than their counterparts who used a mix of the contact- and insulated-rod (hotstick) method (127 versus $83 \text{ V} \cdot \text{m}^{-1}$), although the exposures did not differ statistically. The electric field exposures in the expected low-exposure categories of the blue- and white-collar workers were 5.0 and $5.8 \text{ V} \cdot \text{m}^{-1}$, respectively. Although not statistically significantly different, several categories had exposures lower than the expected low (background) levels: instructors, foremen — underground lines, operator-dispatcher RCC or DCC, and both jobs in nuclear generating stations. When the electric field exposures were expressed as the 20th percentile (correlated at $r = 0.29$ for the arithmetic means and $r = 0.57$ for the geometric means), the most highly exposed trades were forestry workers, with a 20th percentile of $3.3 \text{ V} \cdot \text{m}^{-1}$, followed by emergency men ($1.2 \text{ V} \cdot \text{m}^{-1}$) and equipment electricians in 735 kV substations ($1.1 \text{ V} \cdot \text{m}^{-1}$).

Correlations of exposure indices

At the job-category level, the exposures to magnetic and electric fields were only weakly correlated (arithmetic means $r = 0.34$, geometric means $r = 0.26$). Within each field, however, the patterns of exposure by job category evident in tables 1 and 2 depended little on the specific index of exposure used. Product-moment correlations of alternative indices at the job-category level (tables 3 and 4) showed that, for magnetic fields, the arithmetic mean was highly correlated ($r \geq 0.8$) with all the indices except the 20th percentile, fractions of time spent above 12.4 and $100 \mu\text{T}$, and the geometric mean of the weekly geometric means. The weekly geometric means, however, correlated highly ($r = 0.89$) with the 20th percentile. The arithmetic and geometric means for the electric field also correlated highly with all the electric field indices except the 20th percentile. The rank-order correlations (not shown) were slightly higher, generally, than the product-moment correlations. Our index of rate of change for field time ($\text{dB} \cdot \text{dt}^{-1}$), the minute-to-minute standard deviations, was highly correlated with the arithmetic means of the electric fields ($r = 0.97$) but slightly less so with the arithmetic means of the magnetic fields ($r = 0.80$). Finally, the within- and between-worker components of variation (as geometric standard deviation) were correlated with the arithmetic mean of the magnetic fields at $r = 0.38$ and $r = 0.62$ and with that of the electric

Table 3. Product-moment correlation coefficients between the 60-Hz magnetic field indices for job categories.^a

	AM-AM	AM-MED	GM-AM	GM-GM	Percentiles		Fractions						
					20%	90%	>.2 μT	>.39 μT	>.78 μT	>1.56 μT	>6.25 μT	>12.4 μT	>100 μT
Arithmetic means of arithmetic means (AM-AM)													
Arithmetic means of medians (AM-MED)	0.86												
Geometric means of arithmetic means (GM-AM)	0.92	0.96											
Geometric means of geometric means (GM-GM)	0.69	0.70	0.79										
20th percentile	0.45	0.39	0.50	0.89									
90th percentile	0.93	0.71	0.77	0.51	0.25								
Fraction exceeding 0.2 μT	0.80	0.77	0.84	0.91	0.72	0.65							
Fraction exceeding 0.39 μT	0.84	0.83	0.90	0.93	0.72	0.70	0.97						
Fraction exceeding 0.78 μT	0.86	0.86	0.93	0.92	0.69	0.71	0.93	0.99					
Fraction exceeding 1.56 μT	0.85	0.85	0.93	0.92	0.68	0.68	0.90	0.96	0.98				
Fraction exceeding 6.25 μT	0.92	0.84	0.86	0.49	0.28	0.83	0.60	0.66	0.70	0.70			
Fraction exceeding 12.4 μT	0.79	0.61	0.60	0.16	-0.03	0.82	0.34	0.36	0.39	0.40	0.86		
Fraction exceeding 100 μT	0.55	0.39	0.45	0.09	-0.07	0.49	0.25	0.25	0.28	0.27	0.56	0.59	
Time rate of change index ($_{\text{ww}}\text{S}$)	0.80	0.70	0.72	0.30	0.07	0.70	0.45	0.48	0.51	0.54	0.83	0.85	0.78

^a N = 32 job categories, 465 worker-weeks.**Table 4.** Product-moment correlation coefficients between the 60-Hz electric field indices for job categories.^a

	AM-AM	AM-MED	GM-AM	GM-GM	Percentiles		Fractions	
					20%	90%	>20V $\cdot \text{m}^{-1}$	>78V $\cdot \text{m}^{-1}$
Arithmetic means of arithmetic means (AM-AM)								
Arithmetic means of medians (AM-MED)	0.98							
Geometric means of arithmetic means (GM-AM)	0.99	0.99						
Geometric means of geometric means (GM-GM)	0.75	0.76	0.76					
20th percentile	0.29	0.24	0.26	0.57				
90th percentile	0.90	0.87	0.89	0.82	0.40			
Fraction exceeding 20 V $\cdot \text{m}^{-1}$	0.86	0.87	0.87	0.92	0.45	0.87		
Fraction exceeding 78 V $\cdot \text{m}^{-1}$	0.91	0.90	0.91	0.85	0.29	0.92	0.96	
Time rate of change index ($_{\text{ww}}\text{S}$)	0.98	0.95	0.96	0.66	0.22	0.79	0.80	0.84

^a Forestry workers excluded, N = 31 job categories, 460 worker-weeks.

fields at $r = 0.80$ and $r = 0.22$. The correlations of these indices were lower for the geometric means.

Variation in exposures

Job category explained 49.6% and 59.5% of the variance in the logarithms of the weekly magnetic and electric field means. The variation of the exposure within job categories, as expressed by the crude between-worker geometric standard deviation of the weekly time-weighted average fields (S_g in tables 1 and 2), ranged from 1.1 to 4.2 for the magnetic fields and from 1.3 to 4.6 for the electric fields, but the medians were identical for both types of fields (2.33). When the variation of the daily means was partitioned into within-worker and between-worker components, as expressed by the geometric standard deviations of the within-worker ($_{\text{ww}}S_g$) and between-worker ($_{\text{bw}}S_g$) values, both the magnetic and electric fields showed slightly higher variation for the within-

worker values (median $_{\text{ww}}S_g$ 2.13 for magnetic fields and 2.24 for electric fields) than for the between-worker values (median $_{\text{bw}}S_g$ 1.71 for the magnetic fields and 1.81 for the electric fields).

Discussion

To minimize bias in the exposure estimation, we randomly selected workers to wear exposure meters. Therefore, the collaboration rate of just over 90% was an important achievement. We attribute this rate largely to the contacts established early with the unions and regional management, and to the feedback provided to the workers after their participation. Unfortunately, 22% of the measurements were unusable, due to meter failure in the field (12%), suspicious readings (4%), or unrepresentative conditions (6%). Most of the data losses were

due to problems with early production meters used at the beginning of the study, but we had no reason to believe that the lost measurements were unrepresentative.

Comparison with other reports of exposure in electric utilities

In comparing our results with those of other electric utilities, one must be aware that identical job titles can hide important differences between utilities in job duties, work habits, and equipment. For example, the jobs of distribution linemen and transmission linemen are distinct at Hydro-Quebec, while at many other utilities a single job title covers both types of lines. Even within a single title, different work practices can alter exposures, as seen in this study with the distribution linemen. Last, small yet systematic differences in exposures can be expected when results from a narrow bandwidth meter (eg, Positron) are compared with those from a broadband instrument (eg, EMDEX), the latter being expected to yield higher readings when harmonics are present. The differences from meters are likely to be small, however, in comparison with the differences arising from measurement strategies or from differences in equipment and work practices between utilities.

For jobs with expected low exposure, the mean magnetic fields of 0.15 and 0.16 μT found for blue- and white-collar workers are similar to mean field values reported for similar occupational categories at Electricité de France, where two groups of blue-collar workers had mean exposures of 0.17 and 0.19 μT and white-collar workers had a mean exposure of 0.13 μT (8). White-collar workers at Ontario Hydro had somewhat higher exposures of 0.20 and 0.23 μT , while two groups of blue-collar workers had mean field exposures of 0.14 and 0.50 μT (8). At Southern California Edison, Sahl et al (5) reported mean fields of 0.18 μT for 55 clerical workers and 0.10 μT for five managerial workers. Our 90th percentiles and fractions of time exceeding 0.78 and 6.25 μT are compatible with those of Sahl's expected low-exposure group of clerical workers. Elsewhere in the United States, an arithmetic mean exposure of 0.17 μT has been reported for a group of nonelectrical workers (in Los Angeles County) (17), and 0.15 μT has been recorded for a group ($N = 55$) of telephone utility (AT&T) nonlinear workers (15). When jobs within substations are compared, our values are consistent with those found elsewhere, considering differences in job duties. Mobile operators at Hydro-Quebec travel frequently between substations and had a mean magnetic field of 1.17 μT . For Electricité de France, the equivalent trade had a mean exposure of 0.74 μT . At Ontario Hydro, and Southern California Edison, operators who remained in the substations received a mean exposure of 1.49 μT and 1.78 μT . Substation operators in the Savitz five-utility study, reported by Kromhout et al (18), had a

mean exposure of 0.80 μT (55 workers), a value lower than ours and those at Southern California Edison. The mean magnetic field exposures for Hydro-Quebec distribution linemen are compatible with the mean exposures reported for power-line maintainers at Ontario Hydro (0.52 μT), those reported by Kromhout et al (0.65 μT), and the linemen at Southern California Edison (0.82 μT). Distribution line workers at Electricité de France received considerably lower mean exposures (0.09, 0.21 μT), probably due to the lower proportion of live-line work done by linemen at the utility (P Guénel, INSERM, personal communication). Distribution cable splicers at Hydro-Quebec had a mean magnetic field (1.87 μT) that was similar to the 1.50 μT value given by Kromhout et al, but it was considerably higher than the value reported for distribution cable splicers at Electricité de France, where work practices are presumed to have differed, as has already been described.

Correlations

The pattern of correlations between the arithmetic mean and other summary indices at the job-category level was broadly similar to that observed by Savitz et al (7) and Armstrong et al (4). In contrast to the study by Sahl et al (5), we found that the arithmetic mean of the magnetic field highly correlated with the fractions of time spent above 0.4 μT ($r = 0.84$), 0.78 μT ($r = 0.86$), and 1.56 μT ($r = 0.85$). Sahl's lower correlations (0.5 μT , $r = 0.47$; 1.0 μT , $r = 0.51$) may be a result of calculation from pooled data for all workers within a category. The examination of correlations at the job-category level (7) by Savitz et al also found high correlations of the arithmetic mean with fractions of time spent above 0.2 μT ($r = 0.87$) and above 2.0 μT ($r = 0.95$). Our results corroborate the low correlation noted by Savitz et al between the arithmetic mean and the 20th percentile for electric fields. For magnetic fields, however, our correlation between the arithmetic mean of the magnetic field and the 20th percentile was lower ($r = 0.45$) than the value reported by Savitz et al ($r = 0.77$). In summary, using the combination of arithmetic and geometric means to summarize exposures in job categories will provide good surrogates for all other indices except the fractions of time above 12.4 and 100 μT for magnetic fields and the 20th percentile for electric fields.

Variation of exposures

Our median geometric standard deviation ($_{\text{ww}}S_g$) of 2.13 for the within-worker magnetic field values is slightly lower than the value of 2.6 found by Kromhout et al (18). Our measurements on successive days may have underestimated the within-worker variability if high autocorrelation existed between days. To assess this possibility in our data, we repeated the calculations of the within-worker geometric standard deviations using 2 d of data

from each worker, lagged at 1, 2, 3 and 4 d. The median within-worker geometric standard deviations across all 32 job categories for these lag periods showed a slight increase and therefore suggested some autocorrelation: 1.97, 1.98, 2.08 and 2.26 for magnetic fields and 1.90, 2.30, 2.06 and 2.26 for electric fields. We further examined this possibility by repeating the calculation of the within-worker geometric standard deviations for replicate measurements made on days separated by one to two years in a group of 24 workers chosen randomly from five job categories. Overall, the within-worker geometric standard deviation was 3.19 for magnetic fields (95% CI 2.51–5.26) and 3.42 for electric fields (95% CI 2.68–5.93), higher than the values based on successive days. This finding is consistent with Buringh & Lanting's observation (19) that the variance of occupational exposures increases with the interval between measurements.

Our median between-worker geometric standard deviation ($_{BW}S_g$) for magnetic fields of 1.71, based on weekly means, was slightly lower than the median value of 1.9 found by Kromhout et al, which was based on a shorter (daily) averaging period. This component of variability is useful in estimating the "homogeneity" of exposures in a job category. Rappaport (20) defined a homogeneous group as one for which the ratio of the 97.5th and 2.5th percentiles of the lognormally distributed exposures of a group of workers is no more than two. This criterion is met when the between-worker geometric standard deviation (by variance component; $_{BW}S_g$) is just below 1.2. From tables 1 and 2, it can be seen that only six job categories can be considered homogeneously exposed to magnetic fields: operator (nuclear stations), operators (autonomous network), forestry workers, emergency men, foremen (underground lines), and tree trimmers. For electric fields, only the job categories of foremen (overhead lines) and tree trimmers met the criterion. This finding suggests that future studies of electric and magnetic fields may require different measurement strategies for the two fields.

Variation by meter type and wearing position

We compared electric and magnetic field exposures measured by Positron and IREQ meters after adjustment for job category and found that the magnetic field readings with IREQ meters were, on the average, slightly higher than those from Positron meters, the geometric mean time-weighted average from the IREQ meters being 1.24 times that of the Positron meters. But the difference was small when compared with the exposure differences between or within jobs.

To enhance participation, we had encouraged the participants to wear meters at the belt, identified in our pilot study as a more acceptable position than the shirt pocket, but we gave workers the choice. Of 115 workers who

recorded meter position, only seven (6%) had worn the meter in a shirt pocket. Delpizzo (21) reported that measurements of magnetic fields made at the hip position averaged 14% lower than the whole-body average exposures for activities requiring a generally invariable position. In our study, the jobs having the most static work positions would be white-collar workers and nuclear generating-station operators, for whom the exposures were low, and operators in the hydroelectric generating stations and substations, where exposures were high. For these high-exposure groups, exposure sources are large, and differences in exposure between the hip position and other body locations are expected to be much smaller than those reported by Delpizzo (21).

Concluding remarks

The most highly exposed jobs in this utility were those of substation workers, hydroelectric generating station operators, and cable splicers, with arithmetic mean exposures to 60-Hz magnetic fields exceeding 1 μ T. For perturbed 60-Hz electric fields, forestry workers, equipment electricians in 735 kV substations, and distribution linemen carrying out live-line work with the contact method had arithmetic mean exposures greater than 100 V $\cdot$ m⁻¹. Summarizing exposures at the job category level by the arithmetic and geometric means sacrifices little information on other exposure indices, except the 20th percentile for electric fields and the proportion of time spent above 12.4 μ T and 100 μ T. Our index of the time rate of change was also highly correlated with the arithmetic and the geometric means. But a variety of other possible rate-of-change indices can be envisaged, and it would be useful to understand the patterns of correlations between them. This study has succeeded in characterizing much of the exposure variation between workers, but a fair amount remains unexplained. In a comparison of this and other studies, differences in exposure caused by the use of different meters need to be understood, but the effect is expected to be small compared with differences resulting from job tasks, work sites, and energization of equipment at different utilities. Understanding these sources of variation will help improve the validity of exposure assessments for health studies, for exposure monitoring purposes, and for exposure reduction should that become necessary.

Acknowledgments

We gratefully acknowledge the contributions of Mr Bob Robb, Ms Diane Cyr, and Ms Madeleine Ferron for the fieldwork, computer programming, and identification of job titles. We thank Dr Michel Plante and Ms Betty Tremblay at Hydro-Québec for their assistance in identi-

fying the job titles and Mr Gilbert Turmel and Mr Michel Bourdage at Hydro-Québec's research institute for their technical assistance. We sincerely thank the many Hydro-Québec workers for their diligence in wearing exposure meters and completing activity diaries. Study funding and logistical support were provided by Hydro-Québec.

References

1. Héroux P. A dosimeter for assessment of exposures to ELF fields. *Bioelectromagnetics* 1991;12:241—57.
2. National Radiological Protection Board (NRPB). Electromagnetic fields and the risk of cancer: report of an advisory group on non-ionising radiation. Chilton (Oxon): NRPB, 1992. Documents of the NRPB, vol 3, no 1.
3. Bracken TD. Exposure assessment for power frequency electric and magnetic fields. *Am Ind Hyg Assoc J* 1993;165—77.
4. Armstrong BG, Deadman JE, Thériault G. Comparison of indices of ambient exposure to 60-Hz electric and magnetic fields. *Bioelectromagnetics* 1990;11:337—47.
5. Sahl JD, Kelsh MA, Smith RW, Aseltine DA. Exposure to 60-Hz magnetic fields in the electric utility work environment. *Bioelectromagnetics* 1994;15:21—32.
6. Loomis D, Kromhout H, Peipins LA, Kleckner RC, Iriye R, Savitz DA. Sampling design and field methods of a large, randomized, multisite survey of occupational magnetic field exposure. *Appl Occup Environ Hyg* 1994;9(1):49—52.
7. Savitz DA. Correlations among indices of electric and magnetic field exposures in electric utility workers. *Bioelectromagnetics* 1994;15:193—204.
8. Thériault G, Goldberg M, Miller AB, Armstrong B, Guénel P, Deadman J, et al. Cancer risks associated with occupational exposure to magnetic fields among electric utility workers in Ontario and Quebec, Canada, and France: 1970—1989. *Am J Epidemiol* 1994;139(6):550—72.
9. Deadman JE, Camus M, Armstrong BG, Héroux P, Cyr D, Plante M, et al. Occupational and residential 60-Hz electromagnetic fields and high-frequency transients: exposure assessment using a new dosimeter. *Am Ind Hyg Assoc J* 1988;49(8):409—19.
10. Greene D. Assessment of non-occupational exposures to extremely-low frequency electromagnetic fields in a group of electrical utility workers. Montreal (Québec): McGill University, 1993.
11. Institute of Electrical and Electronic Engineers (IEEE). IEEE standard procedures for measurement of power frequency electric and magnetic fields from AC power lines. New York (NY): Institute of Electrical and Electronic Engineers Inc, 1987. ANSI/IEEE Std 644—1987.
12. Deadman JE. [Letter to editor]. *Am Ind Hyg Assoc J* 1996;57(6):580—3.
13. Land CE, Greenberg LM, Hall CE, Drzyzgula CC. Exact confidence limits for linear functions of the normal mean and variance [computer program]. Bethesda (MD): Radiation Epidemiology Branch, National Cancer Institute / Information Management Systems, 1987. [Adapted by Armstrong BG, McGill University, School of Occupational Health, Montreal 1991].
14. Morgan M, Nair I. Alternative functional relationships between ELF field exposure and possible health effects: report on an expert workshop. *Bioelectromagnetics* 1992;13:335—50.
15. Breyse PN, Matanoski G, Elliott E, Francis M, Kaune W, Thomas, K. 60 hertz magnetic field exposure assessment for an investigation of leukemia in telephone lineworkers. *Am J Ind Med* 1994;26:681—91.
16. Armitage P, Berry G. Statistical methods in medical research. 3rd ed. Oxford: Blackwell, 1994.
17. London SJ, Bowman JD, Sobel E, Thomas D, Garabrant DH, Pearce N, et al. Exposure to magnetic fields among electrical workers in relation to leukemia risk in Los Angeles County. *Am J Ind Med* 1994;26:47—60.
18. Kromhout H, Loomis DP, Mihlan GJ, Peipins LA, Kleckner RC, Iriye R, et al. Assessment and grouping of occupational magnetic field exposure in five electric utility companies. *Scand J Work Environ Health* 1995;21:43—50.
19. Buringh E, Lanting R. Exposure variability in the workplace: its implications for the assessment of compliance. *Am Ind Hyg Assoc J* 1991;52:6—13.
20. Buringh E, Lanting R. Exposure variability in the workplace: its implications for the assessment of compliance. *Am Ind Hyg Assoc J* 1991;52:6—13.
21. Delpizzo V. Misclassification of ELF occupational exposure resulting from spatial variation of the magnetic field. *Bioelectromagnetics* 1993;14:117—30.

Received for publication: 20 October 1995