Estimation of exposures to extremely low frequency electric and magnetic fields

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To my parents and my brother.

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Abstract

The objective of this thesis was to characterize the distribution, variability and determinants of exposures to extremely low frequency (ELF) electric and magnetic fields in environments where no information was previously available, and to advance the methodology of exposure estimation. The thesis is divided into three related papers.

The first paper reports a study of personal ELF field exposure measurements of 465 randomly selected workers in an electrical utility. By job category, arithmetic mean magnetic field exposures ranged from 0.09 to 2.36 μT (electric fields: 2.5 to 400 V/m). ELF magnetic field exposures were highest for substation workers, hydroelectric generating station operators and cable splicers; electric fields were highest for forestry workers, equipment electricians and distribution linemen. Most alternative indices of exposure were highly correlated with the arithmetic or the geometric means ($r \geq 0.8$). Job category explained half of the total variance in logarithms of weekly magnetic and electric field means.

The second paper reports a method developed to estimate past ELF field exposures of the electric utility workers. The present intensities and durations of exposures for tasks were measured, then separately extrapolated to the past based on information from interviews with long-service personnel at the utility. From reconstructed time weighted average (TWA) exposures, magnetic fields were estimated to have increased most over time for substation and distribution-line jobs; the increase for electric fields was less than for magnetic. The method is applicable to other exposures where monitoring records

allow calculation of the intensity and duration of exposures for tasks and estimates of past intensities and durations of exposures for these tasks can be obtained.

In the third paper, the methodology developed in the occupational setting was applied to a study of personal exposures to ELF fields among 365 randomly selected Canadian children. Overall, the arithmetic mean total magnetic field was 0.121 μT (electric field: 14.4 V/m), with magnetic fields highest in Quebec and lowest in Alberta. Magnetic fields were highest at home during the day. Measurements were at their lowest at night but provided the highest correlation with total magnetic field exposure (r=.91). This study found that children's magnetic fields exposures varied substantially between certain provinces (province accounting for 14.7% of the variation) most likely because of differences in the proportion of residences in multiple dwellings, heated electrically or cooled by air conditioning. These attributes were identified as potentially useful predictors of magnetic fields.

Résumé

L'objectif de cette thèse fut d'estimer les expositions aux champs électriques et magnétiques de fréquence extrêmement basse (CEM-FEB) dans des environnements où la connaissances des expositions étaient très limitée. En parallèle, la thèse visait l'avancement de la méthodologie de l'estimation des expositions à ces champs. La thèse est divisée en trois articles connexes.

Le premier article rapporte une étude des expositions individuelles aux champs FEB mesurées sur 465 travailleurs sélectionnés aléatoirement, d'une entreprise de génération, transport et distribution de l'électricité au Québec. Par catégorie de métiers, les moyennes arithmétique des expositions aux champs magnétique variaient de 0.09 à 2.36 μT (champs électriques: de 2.5 à 400 V/m). Les plus hautes moyennes arithmétiques enregistrées pour les champs magnétiques furent enregistrées parmi les travailleurs des postes de transformation, les opérateurs de centrale hydroélectriques et les épisseurs de câbles (champs électriques: les travailleurs de sylviculture, les électriciens d'équipement des postes de transformation et les monteurs de lignes de distribution). La plupart des indices alternatives d'expositions furent fortement correlées avec la moyenne géométrique ou arithmétique ($r \geq 0.8$). En soi, la catégorie de métiers expliquait la moitié de la variance totale des moyennes hebdomadaires des champs magnétiques et électriques.

Le deuxième article rapporte une méthode développée pour estimer les expositions passées aux champs FEB parmi ces travailleurs. Les durées et intensités actuelles

d'expositions pour des tâches ont été mesurées, et extrapolées séparément pour le passé, en se basant sur l'information obtenue par entrevue avec du personnel comptant de nombreuses années de service au sein de l'entreprise. A partir des expositions moyennes pondérées reconstruites pour des périodes passées, il fut estimé que les champs magnétiques étaient plus élevés que par passé pour des catégories de métiers travaillant dans les postes de transformation et avec les lignes de distribution. L'augmentation dans le temps des champs électriques était moindre que pour les champs magnétiques. La méthode décrite est applicable à autres expositions environnementales si l'exposition est mesurée de façon à permettre le calcul du niveau et de la durée des expositions pour des tâches, et les estimations des intensités et des durées peuvent être obtenues pour le passé de façon fiable.

Dans le troisième article, la méthodologie développée dans le milieu professionnel fut appliquée à une étude des expositions individuelles de 365 enfants du Canada exposés aux champs FEB. La moyenne arithmétique des champs magnétiques totaux était de 0,121 µT (champs électriques: 14,4 V/m), avec les plus fortes expositions aux champs magnétiques enregistrées à la résidence durant le jour. Pour les champs magnétiques, les plus faibles expositions furent enregistrées durant le sommeil, mais ces expositions ont donné la plus forte corrélation avec l'exposition totale (r=0,91). Cette étude a démontré des différences importantes d'expositions des enfants aux champs magnétiques d'un province à l'autre (en soi, la province de résidence expliquait 14,7 % de la variabilité) et cette différence semblait dépendre principalement de la proportion des logements faisant partie des bâtiments à logements multiples, chauffés par l'électricité ou rafraîchis par la climatisation.

Preface

This dissertation includes three papers, one accepted for publication and two submitted. Each paper has its own abstract, introduction, literature review, methods, results, discussion and concluding sections, list of references and tables.

Faculty regulations for manuscript-based dissertations are cited below to inform the external reader.

> *"Candidates have the option of including, as part of the thesis, the text of one or more papers submitted or to be submitted for publication, or the clearly duplicated text of one or more published papers. These texts must be bound as an integral part of the thesis.*
>
> *If this option is chosen, connecting texts that provide logical bridges between the different papers are mandatory. The thesis must be written in such a way that it is more than a mere collection of manuscripts; in other words, results of a series of papers must be integrated.*
>
> *The thesis must still conform to all other requirements of the "Guidelines for Thesis Preparation." The thesis must include: A Table of Contents, an abstract in English and French, an introduction which clearly states the rationale and objectives of the study, a review of the literature, a final conclusion and summary, and a thorough bibliography or reference list.*
>
> *Additional material must be provided where appropriate (e.g., in appendices) and in sufficient detail to allow a clear and precise judgement to be made of the importance and originality of the research reported in the thesis.*
>
> *In the case of manuscripts co-authored by the candidate and others, the candidate is required to make an explicit statement in the thesis as to who contributed to such work and to what extent. Supervisors must attest to the accuracy of such statements at the doctoral oral defence. Since the task of the examiners is made more difficult in these cases, it is in the candidate's interest to make perfectly clear the responsibilities of all the authors of the co-authored papers."*

The review of the literature on estimation of exposures to ELF fields is divided among the three papers, according to the subject matter. An explicit statement on who contributed to this thesis work and to what extent is given in Chapter 2: Statement of originality, contribution and co-authorship.

1. Introduction

The production, distribution and use of electrical power give rise to electric and magnetic fields (EMF) within the extremely low frequency (ELF) range from 3 to 300 Hz. The effects on human health of exposure to these byproducts of the electrical power system have been the subject of intense scientific inquiry for the past two decades. One of the main limitations in this inquiry has been the lack of knowledge of exposure levels in the environments under study. Meaningful estimation of ELF-EMF exposures is a vital component of the assessment of risks from ELF-EMF fields and of programmes that seek to reduce exposures to them.

In the fall of 1988, a case-control study of cancer risk among electrical utility workers in Québec, Ontario and France (referred to as the Canada-France study) was initiated by Dr. Gilles Thériault, Director of the Department of Occupational Health, McGill University. The study was funded by three electrical utilities, one of which had just developed a small, wearable electric and magnetic field exposure meter. I pilot tested the meter in a group of electric utility workers in Quebec and wrote a paper describing the pilot study[1] that was instrumental in demonstrating the feasibility of the epidemiological study. Within the epidemiological study, I had responsibility for producing a job-exposure matrix linking electrical utility job titles to exposures to 60-Hz electric and magnetic fields, and; estimating exposures of these workers to confirmed or

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[1] 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):409-419.

suspected occupational carcinogens. From this work, I published a second paper[2] that reported on the method developed for estimating past exposures to these occupational carcinogens. This work allowed the epidemiological study of cancer and exposure to ELF fields to control for the potentially confounding effects of these exposures.

In 1990, a case-control study of childhood cancer risk and exposure to ELF electric and magnetic fields (referred to as the BCCA/McGill study) was initiated by Mary McBride and Dr Richard Gallagher of the British Columbia Cancer Agency, and Dr. Gilles Thériault at McGill. Within this study, I had responsibility for developing the methods for estimating children's exposures to ELF electric and magnetic fields.

These studies, and the ability to monitor exposures over multiple days and at frequent intervals, provided a unique opportunity to estimate exposures in populations for whom virtually no magnetic field exposure data existed, and thus advance exposure estimation beyond the use of simple exposure surrogates such as job titles (for occupational studies) or wire codes and spot measurements (for residential studies). Very little was known about which index of exposure to ELF electric and magnetic fields was important, if any. The detailed measurements provided by the exposure meters provided the first opportunity to calculate and examine the relationships among a wide variety of exposure indices. Further, the ability to measure the intensity and duration of exposures for specific tasks or activities offered the possibility of developing a new method of

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[2] Deadman JE, Church G, Bradley C, Armstrong B, Thériault G. Retrospective estimation of exposures to confirmed or suspected carcinogens in an electrical utility. Appl Occup Environ Hygiene 1995;10:856-971.

extrapolating present exposure measurements to the past, of particular usefulness to epidemiological studies of cancers with long latency periods. Lastly, an improved understanding of exposure variability between individuals and over time is essential to increasing the validity of exposure assessments and to the efficient planning of control measures.

Objectives and rationale

The objective of this thesis was to estimate ELF-EMF exposures in occupational and non-occupational environments where little was previously known about exposures, and to advance the methodology of exposure estimation.

The thesis work is described in three papers whose objectives and rationale are given below.

Paper 1	Assessment of exposures to 60-Hz magnetic and electric fields at a Canadian electric utility
Objective	*To estimate exposures of electrical utility workers in Québec to extremely low frequency (ELF) magnetic and electric fields.*
Rationale	In epidemiological studies of ELF fields, the estimates of exposure should be as accurate as possible. Since everyone is exposed to ELF fields to some extent, definition of a reference low-exposure group is essential. The biologically relevant index of exposure, if any, is uncertain and there is no known suitable biological marker of exposure. Estimation of ELF field exposures thus requires careful consideration of the relationships among

many possibly important exposure metrics and their variability. Variety in the extent and magnitude of fields from different sources of exposure can produce large spatial variations in field levels. In the occupational setting, exposures exhibit large variations during a day, between days, and between individuals within a group. Since exposures of electrical utility workers were expected to be among the highest that could be encountered in the workplace, this group was selected for the epidemiological study of cancer risks. Therefore it was important to characterize their exposures accurately and in a way that would allow evaluation of variety of alternative exposure indices.

Paper 2	Task-based estimation of past exposures to 60-Hz magnetic and electric fields at an electric utility
Objective	*To estimate past exposures of electric utility workers in Québec to extremely low frequency (ELF) magnetic and electric fields.*
Rationale	The long latency periods of many cancers make retrospective exposure assessment a necessity in epidemiological studies. The difficulties involved in accurately estimating past exposures have resulted in the development of this area as a distinct speciality marrying industrial hygiene and epidemiology. No retrospective estimation of ELF fields had ever been undertaken for electrical utility workers or other groups exposed to ELF fields. Retrospective estimation of exposures to these fields presents a particular set of difficulties. In particular, the exposures were not memorable, were not generally measured in the past and their determinants have not

been well characterized. In addition, self-reporting of historical exposure is not possible because ELF fields are not detectable by humans at levels found in most environments, and potential study subjects are often deceased. Therefore, it was important to develop a method for estimating past exposures.

Paper 3: Exposures of children in Canada to 60-Hz magnetic and electric fields

Objective *To characterize exposures of Canadian children to 60-Hz magnetic and electric fields and explain the variability of exposures.*

Rationale ELF magnetic field exposures of children are of particular concern because the epidemiological evidence for an association with leukemia is strongest in this group. No large-scale assessments of children's exposures to ELF fields had ever been conducted. Exposures of control children randomly selected from the general population should provide a reliable portrait of ELF field exposures in children. Magnetic fields can vary substantially between geographic locations and over time as a function of power use in and around the environment under study. Thus, it was important to characterize the distribution and variability of children's ELF field exposures and investigate the determinants of exposure.

2. Statement of originality, contribution and authorship

This thesis provides new knowledge of the distribution and variability of exposures to extremely low frequency (ELF) electric and magnetic fields (EMF) among electric utility workers and among children. It provides an improved understanding of strategies for estimating present and past exposures to these fields in these and other populations.

For the Canada-France study, I was responsible for the design and execution of the present and past exposure estimation programmes. Although working within the study, I developed thesis objectives that were broader than those for the exposure estimation component of the epidemiological study, in that they sought to explain variability in exposures, to examine alternative indices of exposure and to develop a novel method of estimating past exposures.

In collaboration with Dr Thériault, I wrote a protocol for the development of the job-exposure matrix, in which I developed a sampling strategy that pioneered the use of a newly developed exposure meter and that was the first to use detailed diaries of workers' tasks. This exposure study was the first to estimate occupational exposures to ELF fields in this environment on a large-scale from randomly chosen workers. For the estimation of past exposures, I wrote a protocol which described an original task-based method for breaking down exposures by task and by location and for separating exposures into their intensity and their duration. This was the first detailed examination of tasks and locations that most influenced exposures in this industry. The past exposure estimation method further innovated by separating the extrapolation of task exposure duration and task exposure intensity for past conditions.

I was responsible for obtaining approval for the measurement strategy from Hydro-Quebec senior management and its unions, establishing fieldwork contacts, conducting fieldwork, reporting results to workers and producing the job-exposure matrix. Data-processing and data checking were under my supervision. The interviews with long-service workers and other utility experts were conducted under my supervision.

For the British-Columbia Cancer Agency and McGill University study, I had responsibility for estimating children's exposures to ELF fields. Although working within this study, I developed thesis objectives that went beyond those of the epidemiological study to include the characterization of the distribution, the variability and determinants of exposures among children. The study of children's exposures to ELF fields was the first large-scale assessment of exposures in this group to use personal exposure measurements and activity diaries. It was the first investigation of the geographical and seasonal variations of children's ELF-EMF exposures in Canada and the first study to examine characteristics of Canadian housing as possible explanatory variables.

I carried out all the statistical analyses, including computation of alternative exposure indices, computation of within and between-person variability of exposures, computations of correlations, and all descriptive analyses. I wrote the literature review for each paper and wrote the three papers. The papers were co-authored by Dr. B. Armstrong (1, 2, 3), Dr. G. Thériault (1, 2, 3), Mr. G. Church and Ms. C. Bradley (2), Ms. ML McBride and Dr. R. Gallagher (3), who contributed as follows:

Dr. B. Armstrong as my thesis supervisor, continually monitored my progress, oversaw the statistical aspects of the work, and revised the substance and style of the manuscripts.

Dr. Gilles Thériault as the principal investigator of the Canada-France study, obtained permission from Hydro-Québec for this thesis work, and allowed me to use the exposure data. He reviewed and commented on the manuscripts.

Mr. G. Church and Ms. C. Bradley carried out most of the interviews and historical documentation at Hydro-Québec, under my supervision.

Ms ML McBride and Dr. R. Gallagher as principal investigators of the BCCA/McGill study allowed me to use the exposure data, and reviewed and commented on the childhood exposures manuscript.

Published: Deadman JE, Armstrong, BG, Thériault GP. Assessment of exposures to 60-Hz magnetic and electric fields at a Canadian electrical utility. Scand J Work Environ Health 1996;22:415—424.

3. Assessment of Exposures to 60-Hz Magnetic and Electric Fields at a Canadian Electrical Utility

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Abstract

Objectives To estimate exposures of electrical utility workers in Québec to extremely low frequency (ELF) magnetic (B) and electric (E) fields.

Methods Personal exposures to ELF- B and E fields were measured on workers randomly selected from 32 job categories at Hydro-Québec. Weekly arithmetic (AM) and geometric means (GM), and other indices of exposure were estimated from 465 worker-weeks of data.

Results By job-category, ELF magnetic AM exposures ranged from 0.09 to 2.36 μT. ELF electric AM exposures ranged from 2.5 to 400 V/m. Within each field, correlations of either AMs or GMs 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 E, and proportion of time above 12.4 and 100 μT. Day-to-day variation of exposure was greater than variation between workers: median between-day and between-worker components of variance (as GSDs) by job-category were 2.13 and 1.71 for B fields (2.24 and 1.81 for E).

Conclusions Substation workers, hydroelectric generating station operators, and cable splicers, showed the highest AM 60-Hz B fields, above 1 μT. For 60-Hz E fields, forestry workers, equipment electricians in 735 kV substations, and distribution linemen (contact method) had AM exposures greater than 100 V/m. Of the total variance in logarithms of weekly magnetic and electric field means, job category explained 49.6% and 59.5% respectively.

1. Introduction

Assessment of exposures 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 exposures to be monitored in substantial detail over one or more work shifts. (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 footing. Further, knowledge of the variability of exposures between workers and over time is essential to increasing the validity of exposure assessments and in planning control measures. Several surveys have been conducted in the past to assess exposures to power-frequency electric and magnetic fields in electric utilities and other occupational environments, using area and source measurements, or personal monitoring, and these have been reviewed elsewhere (2)(3). In an earlier paper, (4) we summarized workers' ELF field exposures by the arithmetic and geometric means as these 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 US electric utility industry (5)(6) for epidemiological studies of ELF fields and cancer. The study of magnetic field exposures at Southern California Edison (SCE) by Sahl et al, using a data-logging meter, confirmed the high correlation of either the arithmetic and 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 (microtesla) might also be useful in discriminating occupational groups. In the study of five US electrical utilities by Savitz et al, a time-averaging meter was used to estimate arithmetic and geometric means of daily arithmetic mean magnetic fields for workers chosen randomly from 28 job groups. This study also found high correlations between either the arithmetic and geometric means and several alternative indices at the job category level, for both magnetic and electric fields. (7)

To provide exposure estimates for subjects of the Québec portion of the Canada-France study of EMF and cancer in electrical utility workers (8), we conducted an extensive survey of personal exposures 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 variation in exposures within-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 exposures were judged to have differed sufficiently from the present to justify separate estimation of them. For this, we developed a task-based approach to correct current exposure estimates, that are reported in the next chapter of the thesis.

2. Methods

2.1 Grouping of jobs for the job-exposure matrix

An industrial hygienist and an occupational physician at the utility classified all the utility's job titles (2,466) into two groups: an expected-low exposure group in which duration of daily proximity to energized equipment was estimated as less than 15 minutes (2,300 jobs) and a second group expected to be exposed at levels higher than the expected-low 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 2,300 jobs with expected-low exposures were subdivided into blue-collar and white-collar categories, and the 166 jobs with expected high exposures were grouped into 30 job categories (Tables 1 and 2).

2.2 Sampling strategy

The goal of the epidemiological 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 non-occupational 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 of arithmetic mean exposures during work and during sleep of r=0.07 for magnetic and r=0.06 for electric fields. Comparing work and non-occupational activities other than sleep, correlations were r=.03 for magnetic and r=.17 for electric. (10)

The measurement campaign covered nine of the utility's ten administrative regions, 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 ensured contact with workers, follow-up and replacements. In three regions, we gave utility representatives the option of randomly choosing work teams of 3 to 5 workers, instead of individuals. This was done at the utility's request, to prevent the organizational difficulties that selection of individual workers from different teams in different geographic locations would have caused. The option of sampling teams was offered for 10% of 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 the pilot study, was to measure occupational exposures over 5 days 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, the expected intensity and variability of exposures, and were revised during the campaign based on measured intensity. In nine of the categories, fewer than 10 workers were measured. Five job categories had arithmetic mean magnetic fields with an upper 95% confidence interval less than 1.0 μT based on samples of 5 or 6 workers, and sampling was truncated for these. Two categories did not appear among the case and control jobs (forestry workers, tree trimmers) and sampling was also suspended. Time constraints prevented reaching the minimum requirement for two categories: hydroelectric generation foremen and licensed electricians.

2.3 Measurement of magnetic and electric fields

Personal exposure meters (Positron model 378108) and prototype meters developed by Hydro-Quebec's research institute (IREQ dosimeters) 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) 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, using a Helmholtz coil arrangement. No drift in meter response was detected. An error of up to 10% difference between readings and bin edge values was accepted. Primary calibration of 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.

2.4 Data analysis

After transferring exposure data to computer, the software-displayed time of the calibration mark made by the portable magnetic field generator was checked, and discrepancies of over five minutes were resolved by adjusting the start time on the data file. Time information recorded on workers' activity diaries was checked for consistency with displayed meter data. Work start and stop times were noted primarily from the diaries, but checked using the software's electric field display 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 six hours of magnetic and electric field data consistent with the activity diary, the day was considered valid. Using meter software, exposure data for each valid day was then summarized into a "histogram" file, containing the number of measurements in each of the 16 bins for both fields. The mean duration of measurements for all 465 workers was 5.7 days, as some workers wore meters for more than the five required days. There were 12 workers for whom two days of valid data were retained, and four for whom only one day 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, but using the logarithms of the bins' midpoints and taking the antilog of the final result. Out of 623 workers, we obtained collaboration from 563. Of these, data from 67 participants were lost to 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 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 just over two, on average, with 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 early software used to display mean field values recorded by prototype dosimeters. (12)

As the focus of the epidemiological 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 95% confidence intervals 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/m, and 0.2, 0.39, 0.78, 1.56, 6.25, 12.4 and 100 μT) and the 20th and 90th percentiles. Cutpoints were chosen to be as compatible as possible with other reports, but the meters' bin boundaries imposed some constraints. The possibility that biological effects of magnetic fields may be related to the time rate of change (dB/dt) (14) lead Breysse et al (15) to measure the average difference between successive one-minute measurements. From our data, we devised a surrogate for dB/dt by estimating the within-person, minute-to-minute standard deviations of magnetic and electric fields for each worker.

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

3. Results

Arithmetic and geometric mean 60-Hz magnetic and electric fields are shown in Tables 1 and 2 respectively, by job category. The geometric means shown are the geometric mean of workers' weekly *geometric* means, as reported in the cancer study (8). For clarity, indices correlated at $r \geq 0.8$ are not shown. A complete set of results is available from the authors.

3.1 Magnetic fields

From Table 1, magnetic field exposures were highest overall for substation jobs, with arithmetic mean exposures ranging from 1.05 μT for maintenance workers, to 2.36 μT for equipment electricians in unstaffed substations of 735 kV or lower voltage. Equipment electricians' exposures result from the installation, maintenance and servicing of electrical apparatus in substations, typically transformers, circuit breakers and disconnect switches. Although electricians usually worked on de-energized 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. These 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. Average exposure over these two locations was 2.5 μT. The remainder of the operators' time was spent in the control room, at an average 1.1 μT, performing functions such as monitoring the generating units' output and operating remote-controlled devices. Exposures of equipment electricians in these stations (0.99 μT) were lower than the operators, as less time was spent near energized equipment. Equipment mechanics who repair, maintain, and install mechanical components of power-house and substation equipment, spent less time close to energized equipment than the electricians, with exposures correspondingly lower: 0.77 μT.

Within the other major facilities at the utility, magnetic field exposures showed considerable variability across job categories. The highest exposures were found in trades working near energized conductors, with exposures generally scaling with the number of conductors, current capacity, and the time spent near them. For example, transmission and distribution cable splicers (1.80, 1.87 μT) install, maintain and repair underground cables, spending on average 15 h/wk in underground cable vaults. While most cable splicers' work is done on de-energized cables, other cables in the vaults are usually live. Mean exposures while in the distribution cable vaults were 4.77 μT. When exposures were expressed as the mean duration of time above 100 μT for a 40-h work week (correlated at r=0.55 with the AM, r=.09 with the GM), 17 job categories showed exposure above this level. The trades with the highest weekly durations above 100 μT were splicers working on transmission cables (5 min/wk), substation maintenance workers and licensed electricians (3 min/wk).

Measurements of the blue-collar and white-collar job categories confirmed expectations, showing low and similar magnetic fields: 0.15 and 0.16 μT. Magnetic field exposures were also low for several other groups, including nuclear generating station operators, estimators, and foremen for overhead and underground line workers.

3.2 Electric fields

From table 2, 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 V/m, (95% CI: 126, >1000 V/m) were registered for forestry workers (who did not contribute subjects to the case-control study) who had spent about 30 hours per 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 V/m. Other trades involving extended periods near live unshielded conductors are the two categories of substation equipment electricians (122 V/m and 52 V/m) and distribution linemen. As expected, distribution linemen who handle live wires mainly by the insulated-glove (contact) method were more highly exposed than their counterparts who use a mix of the contact- and insulated-rod (hotstick) method, (127 vs 83 V/m), although exposures were not statistically different. Electric field exposures in the expected-low categories of blue and white collar workers were 5.0 and 5.8 V/m respectively. Although not statistically significantly different, several categories had exposures lower than the expected-low (background) levels: instructors, foremen - underground lines, operator / dispatcher RCC/DCC, and both jobs in nuclear generating stations. When electric field exposures were expressed as the 20th percentile (correlated at $r=.29$ with the AM, $r=.57$ with the GM), the most highly exposed trades were forestry workers, with a 20th percentile of 3.3 V/m, followed by emergency men (1.2V/m), and equipment electricians in 735 kV substations (1.1 V/m).

3.3 Correlations of exposure indices

At the job-category level, exposures to magnetic and electric fields were only weakly correlated (arithmetic means $r = 0.34$, geometric means $r = 0.26$). Within each field, though, the patterns of exposure by job category evident on Tables 1 and 2 depended little on specific index of exposure used. Product-moment correlations of alternative indices at the job category level (tables 3 and 4) show that for magnetic fields, the arithmetic mean was highly correlated ($r \geq 0.8$) with all indices except the 20th percentile, fractions of time spent above 12.4 and 100 μT, and the geometric mean of the weekly geometric means. The latter index, however, correlated highly ($r=0.89$) with the 20th percentile. Electric field arithmetic and geometric means also correlated highly with all electric field indices except the 20th percentile. Rank-order correlations (not shown) were slightly higher, generally, than the product-moment correlations. Our index of field time rate of change (dB/dt), the minute-to-minute standard deviations, were highly correlated with arithmetic means for electric fields (r=.97) but slightly less so for magnetic (r=0.80). Finally, the within- and between-worker components of variation (as GSDs) were correlated with arithmetic mean magnetic fields at r=.38 and r=.62, and for electric fields, r= .80 and r=.22, respectively. Correlations of these indices with geometric means were lower.

3.4 Variation in exposures

Job category explained 49.6% and 59.5% of the variance in logarithms of weekly magnetic and electric field means. Variation of exposure within job categories, as expressed by the crude between-worker GSDs of the weekly TWA fields (S_g in Tables 1 and 2), ranged from 1.1 to 4.2 for magnetic and from 1.3 to 4.6 for electric, but the medians were identical for both fields (2.33). When variation in daily means was partitioned into within-worker and between-worker components, as expressed by the GSDs within workers (${}_{WW}S_g$) and between workers (${}_{BW}S_g$), both magnetic and electric fields showed slightly higher variation within workers (median ${}_{WW}S_g$: B=2.13, E=2.24) than between workers (median ${}_{BW}S_g$: B=1.71, E=1.81).

4. Discussion

To minimize bias in the exposure estimation, we selected workers randomly to wear exposure meters. Given this, the collaboration rate of just over 90% was an important achievement. We attribute this largely to the contacts established early on with the unions and regional management, and to the feedback provided to workers following 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.

4.1 Comparison with other reports of exposures in electric utilities

In comparing these results with 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 here with the distribution linemen. Lastly, small yet systematic differences in exposures can be expected when comparing results from a narrow bandwidth meter (e.g., Positron) with those from a broadband instrument (e.g., EMDEX), with the latter expected to yield higher readings when harmonics are present. Differences from meters are likely to be small, however, in comparison with differences arising from measurement strategies, or from differences in equipment and work practices between utilities.

For jobs with expected low exposures, the mean magnetic fields of 0.15 and 0.16 μT found for blue and white-collar workers are similar to mean fields reported for similar occupational categories at Electricité de France (EDF), where two groups of blue collar workers had mean exposures of 0.17 and 0.19 μT, and white-collar workers showed a mean exposure of 0.13 μT (8). White-collar workers at Ontario Hydro (OH) had somewhat higher exposures of 0.20 and 0.23 µT, while two groups of blue-collar workers showed mean fields of 0.14 and 0.50 µT (8). At Southern California Edison (SCE), Sahl et al (5) reported mean fields of 0.18 µT for 55 clerical workers, and 0.10 µT for 5 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 US, arithmetic mean exposures of 0.17 µT have been reported for a group of non-electrical workers in Los Angeles county (17), and 0.15 µT for a group (n=55) of telephone utility (AT&T) non-line workers. (15) Comparing jobs within substations, our values are consistent with those found elsewhere, considering differences in job duties. Mobile operators at Hydro-Quebec (HQ) travel frequently between substations and had a mean magnetic field of 1.17 µT. For EDF, the equivalent trade had a mean exposure of 0.74 µT. At OH, and at SCE, operators who remain in the substations received a mean exposure of 1.49 µT and 1.78 µT. Substation operators in the Savitz 5-utility study, reported by Kromhout et al (18) had a mean exposure of 0.80 µT (55 workers), lower than our values and those at SCE. Mean magnetic field exposures for HQ distribution linemen are compatible with the mean exposures reported for power-line maintainers at OH (0.52 µT), those reported by Kromhout et al (0.65 µT) and the linemen at SCE (0.82 µT). Distribution line workers at EDF 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). HQ distribution cable splicers mean magnetic field (1.87 µT) was similar to the 1.50 µT value given by Kromhout et al, but considerably higher than the value reported for EDF distribution cable splicers, where work practices are presumed to have differed as described above.

4.2 Correlations

The pattern of correlations between the arithmetic mean and other summary indices seen here at the job-category level is broadly similar to those observed by Savitz et al (7), and Armstrong et al (4). In contrast to the study by Sahl et al (5), we find that the arithmetic mean magnetic field correlates quite highly with the fractions of time spent above 0.4 μT (r=.84), 0.78 μT (r=.86) and 1.56 μT (r=.85). Sahl's lower correlations (0.5 μT, r=.47; 1.0 μT, r=.51) may be a result of calculation from pooled data for all workers within a category. The examination by Savitz et al of correlations at the job category level (7) also found high correlations of the AM with fractions of time spent above 0.2 μT (r=.87) and above 2.0 μT (r=.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 magnetic field arithmetic mean and the 20th percentile was lower (r=.45) than the value reported by Savitz et al (r=.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, for magnetic fields, the fractions of time above 12.4 and 100 μT, and for electric fields, the 20th percentile.

4.3 Variation of exposures

Our median within-worker magnetic field GSD ($_{ww}S_g$) of 2.13 is slightly lower than the value of 2.6 found by Kromhout et al (18). Our measurements on successive days may have underestimated within-worker variability if there was high autocorrelation between days. To assess this in our data, we repeated calculations of the within-worker GSDs using two days of data from each worker, lagged at 1, 2, 3 and 4 days. The median within-worker GSDs across all 32 job categories for these lag periods showed a slight increase, suggesting 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. We further examined this by repeating the calculation of the within-worker GSDs for replicate measurements made on days separated by one to two years, on a group of 24 workers chosen randomly from five job categories. Overall, the within-worker GSDs were 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 is consistent with Buringh and Lanting's observation that the variance of occupational exposures increases with the interval between measurements. (19)

Our median between-worker GSD (${}_{BW}S_g$) for magnetic fields of 1.71, based on weekly means, is 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) defines a homogeneous group as one where 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 GSD (by variance component; ${}_{BW}S_g$) is just below 1.2. From Tables 1 and 2, only six job categories could be viewed as 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 meet the criterion. This suggests that future studies of electric and magnetic fields may require different measurement strategies for the two fields.

4.4 Variation by meter type and wearing position

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

To enhance participation, we had encouraged 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 were on average 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 exposures are low, and operators in hydroelectric generating stations and substations, where exposures are 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.

5. Conclusion

The most highly exposed jobs in this utility were substation workers, hydroelectric generating station operators, and cable splicers, with arithmetic mean exposures to 60-

Hz magnetic fields exceeding 1 μT. 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/m. 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 μT and 100 μT. 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 comparing 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.

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Table 1. Occupational exposures to 60-Hz magnetic fields by job category at Hydro-Québec

Job category	N	Arithmetic mean (Am_{am}) (μT)	(95% CI)	S_g	Geometric mean (Gm_{gm}) (μT)	Minutes / week[*] >12.4 μT	Minutes / week[*] >100 μT	$_{BW}S_g$	$_{WW}S_g$
Expected low exposure jobs									
Blue collar jobs[†]	15	0.15	(0.10, 0.31)	2.39	0.03	2.9	0.2	1.80	1.88
White collar jobs[‡]	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, autononous 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 ≤ 735 kV	18	0.60	(0.44, 0.90)	1.90	0.08	14.9	0.2	1.42	3.00
Substation									
Equipment electrician ≤ 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 subst	22	1.78	(1.45, 2.30)	1.62	0.54	16.2	0.1	1.51	1.76
Maint. worker, civil & mech. engin.	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, 735kV substation	12	1.78	(1.00, 4.44)	2.52	0.76	8.5	-	1.94	2.15
Technician, automatic control/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 & 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/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								

Legend

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/dt)

$_{BW}S_g$: geometric standard deviation between-workers (by variance components)

$_{WW}S_g$: geometric standard deviation within-workers (by variance components)

[*] assuming a 40-hr work week

[†] *blue collar jobs:*

Clerk, accounting / judicial / mail / stores / data entry
Meter inspector, Storekeeper
Mechanic, vehicles and equipment
Toolkeeper
Technician, planning/ management

[‡] *white collar jobs:*

Agent, Division head, Section head, Shift supervisor
Consultant, systems management / personnel
Engineer
Commercial representative

[§] RCC = regional control centre; DCC = distribution control centre

Table 2. Occupational exposures to 60-Hz electric fields by job category at Hydro-Québec

Job category	N	Arithmetic mean (Am_{am}) (V/m)	(95% CI)	S_g	Geometric mean (Gm_{gm}) (V/m)	20th %ile (V/m)	$_{BW}S_g$	$_{WW}S_g$
Expected low exposure jobs								
Blue collar jobs[†]	15	5.0	(3.8, 7.6)	1.76	1.3	0.5	1.55	1.57
White collar jobs[‡]	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 st.	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, autononous 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 ≤ 735kV	18	58.0	(38.4, 119.4)	2.51	2.4	0.4	1.77	4.44
Substation								
Equipment electrician, ≤ 735kV	29	52.1	(35.8, 158.9)	3.90	1.8	0.6	3.01	3.10
Equipment electrician, 735kV	22	122.4	(78.1, 268.5)	2.91	3.6	1.1	2.55	2.96
Maint.worker, civil /mech. engin.	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, 735kV substation	12	36.9	(17.1, 416.2)	4.57	2.1	0.7	3.03	3.18
Technician, autom. control/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 / 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/dispatcher RCC/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							

Legend

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/dt)

$_{BW}S_g$: geometric standard deviation between-workers (by variance components)

$_{WW}S_g$: geometric standard deviation within-workers (by variance components)

[†] *blue collar jobs:*
Clerk, accounting / judicial / mail / stores / data entry
Meter inspector, Storekeeper
Mechanic, vehicles and equipment
Toolkeeper
Technician, planning/ management

[‡] *white collar jobs:*
Agent, Division head, Section head, Shift supervisor
Consultant, systems management / personnel
Engineer
Commercial representative

[§] RCC = regional control centre; DCC = distribution control centre

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

					Percentiles		Fractions						
	AM-AM	AM-MED	GM-AM	GM-GM	20%	90%	>.2µT	>.39µT	>.78µT	>1.56µT	>6.25µT	>12.4µT	>100µT
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 percentiles	0.45	0.39	0.50	0.89									
90th percentiles	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 ($_{ww}S$)	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

* (n=32 job categories, 465 worker-weeks)

Table 4. Product-moment correlation coefficients between 60-Hz electric field indices for job categories*

					Percentiles		Fractions	
	AM-AM	AM-MED	GM-AM	GM-GM	20%	90%	>20V/m	>78V/m
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 percentiles	0.29	0.24	0.26	0.57				
90th percentiles	0.90	0.87	0.89	0.82	0.40			
Fraction exceeding 20V/m	0.86	0.87	0.87	0.92	0.45	0.87		
Fraction exceeding 78V/m	0.91	0.90	0.91	0.85	0.29	0.92	0.96	
Time rate of change index ($_{ww}S$)	0.98	0.95	0.96	0.66	0.22	0.79	0.80	0.84

* (forestry workers excluded, n=31 job categories, 460 worker-weeks)

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4. Task-Based Estimation of Past Exposures to 60-Hz Magnetic and Electric Fields at an Electrical Utility

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Abstract

Objectives To estimate past exposures of electric utility workers in Québec to extremely low frequency (ELF) magnetic (B) and electric fields (E).

Methods Present intensities and durations of exposures for tasks or work locations in 14 job categories were measured. Past task/location intensities were extrapolated from the present based on interviews with long-service workers and utility personnel. Past task/location durations were estimated by long-service workers. TWA exposures for jobs were reconstructed for past periods from the intensity and duration estimates.

Results Magnetic fields were estimated to have increased most over time for substation and distribution-line jobs. For substation jobs, ratios of magnetic fields in 1945 to those in 1990 ranged from .42 to .69; distribution-line jobs ranged from .36 to .94. For electric fields in substations, the estimated increase over time was less than for magnetic: 1945/1990 ratios ranged from .59 to .88. For distribution line jobs, ratios of electric fields in 1945/1990 were less than 1.0 in four cases (.6 to .89), more than 1.0 in three others (1.13 to 2.01) and unchanged in one.

Conclusions Reconstruction of TWA exposures allowed changes in the intensity and the duration of exposures to be considered separately. Documentation of intensity and duration of exposures for tasks allows reconstruction of exposures for jobs that have ceased to exist. The method is applicable elsewhere if: 1/ exposure monitoring records allow calculation of the level and duration of exposures for tasks or locations, and 2/ estimates of past durations and intensities of exposures can be reliably obtained.

1. Introduction

Estimation of exposures in retrospective epidemiological studies presents a considerable industrial hygiene challenge. The estimates must represent historical conditions as closely as possible and often no historical records are available to guide the process. For electrical utility workers exposed to extremely low frequency (ELF) electric and magnetic fields (EMF), documentation of electric, then magnetic, field exposures only began to gather momentum in the late 1970s following reports of health effects in substation workers. (1)(2) Exposure data from before 1970 are rare. Where historical data are absent and potential study subjects are deceased, alternative exposure assessment methods include the use of job titles, individual exposure assessment by experts, and job-exposure matrices. (3) For the Canada-France study of cancer in electrical utility workers and ELF fields (4) we had used a job-exposure matrix (5) to estimate present exposures. We required a method of estimating past exposures that minimized subjectivity. Estimation of present exposures has been greatly simplified with the arrival of personal monitors. (6)(7) When used to sample exposures at short intervals, these monitors provide detailed information not only on the intensity but also the duration of exposures. Further, the measurement record can be broken down into the tasks performed during the monitoring. Under a task-TWA (time-weighted average) model (8) the intensity and duration of exposures for present tasks can be estimated. To determine how historical exposures of the workers in the Quebec portion of the Canada-France study were likely to have differed from the present, we reviewed changes in tasks and locations for 32 job categories at Hydro-Quebec that might have affected ELF-EMF intensities and durations of tasks. For jobs thought likely to have differed substantially from the present, we reconstructed exposures for the years 1945 to 1990.

The reconstruction consisted of separate estimation of the present intensities and durations of exposures for tasks and locations, followed by extrapolation to past conditions. We report here on the estimation method and the results for job categories at Hydro-Québec.

2. Methods

At the time of this study, Hydro-Quebec employed 22,000 workers in 10 geographic regions and at the head office in Montreal. In 1990, regions were essentially producers or distributors of electricity, but some had maintained unique work methods typical of the smaller utilities that existed before nationalization of the electric utility industry in 1966. Interviews with workers in job categories exposed to ELF-EMF were carried out in four of the distribution regions and two of the production regions. Eighty-eight percent of the subjects in the cancer study had worked in these six regions.

2.1 Estimation of present exposure intensities and durations for tasks or locations

Exposures to ELF-EMF in a job result from tasks in which the worker is close to energized lines or equipment. Since these sources are generally in fixed locations such as substations, generating stations or transmission line corridors, classifying tasks by the type of location where the task is done is practical. Generally, average exposure intensity for a given task in a specific location will be similar across workers if the equipment and work procedures are also similar. Diverse activities can also be grouped by location in cases where the general environment and not the activity determines the intensity of exposure; this is the case for office work, and activities such as lunch and coffee breaks.

For job categories in which exposures were judged as likely to have differed substantially from the measured 1990 values (Table 1) the monitoring records of between five and 22 workers were randomly selected from all workers in the trade whose exposures had been measured. Monitoring records were used to estimate the present intensities and the durations of exposures for tasks within jobs. These records consisted of the minute-to-minute readings of ELF magnetic and electric fields over a work week and the worker's log sheet that provided the start and stop times and descriptions of tasks carried out during the week. For each task noted on the log sheet (or location if it was judged that the location and not the task determined the exposure), arithmetic mean ELF magnetic and electric fields were calculated and task durations were recorded, using the Positron meter software. (5)

These estimates were classified into task categories by general types of activity or location and the voltage level, when this had been noted (information on line loading at the time of measurements had seldom been recorded by workers). For each task or location category, weighted means were calculated, with weights provided by the measurement times of the individual tasks. Weighted means were expected to be more representative and less variable than unweighted means. We calculated weighted means for each voltage level, and for all voltage levels combined (example for distribution linemen shown in Table 2). Calculation of confidence intervals that fully respect the weighting of measurements by time over which each measurement was made, and the highly skewed distribution both within and between measurements is problematic. To estimate sampling variability we used an approximate method for unweighted means of lognormally distributed values.(9)

2.2 Estimation of past exposure durations and intensities for tasks or locations

Of the 32 job categories derived for the Hydro-Quebec job-exposure matrix, (5) we sought to identify those in which past exposures might have differed substantially from the measured 1990 values, for any five-year period between 1940 and 1990. We first reviewed annual reports and newsletters at the utility for any historical descriptions of jobs and equipment. Unfortunately, these sources had not been systematically classified and a thorough examination would have exceeded the time limitations of the study. Clearly, long-service employees would be the main resource for information on past exposure durations and likely exposure intensities. Consequently, during a five-month period (May - September 1991) about 100 long-service workers and some retired employees at Hydro-Quebec were interviewed to identify changes in tasks or equipment that might have affected the intensity or duration of exposures. To maximize collaboration at the utility, we first sought commitments to the interview process from senior management. Senior managers enrolled regional managers and supervisors for the 32 job categories, and informed them of the goals of the study and the type of information required. Regional managers were asked to provide the names of long-service employees and to help in organizing meetings with them. Once a meeting was set up for a group of study participants, the long-service workers were questioned about job titles used in the past, particularly specialization within the trade; changes in job duties and equipment over time (particularly voltages and amperages), changes in work locations and arrangement of the job site (i.e., time spent in different locations); and regional differences in the job category.

2.2.1 Estimation of past exposure durations for specific tasks or locations

From the monitoring data, we prepared job profiles listing the task and location categories and the durations of time spent in them in 1990. The use of task categories rather than individual tasks to build a job profile simplified the reconstruction process. During interviews, workers were only required to comment on the durations of time spent in a set of task categories in the past, instead of time spent at many individual tasks. Job profiles were presented to each group of long-service workers who were asked to estimate the time spent at the listed tasks over the years back to 1945. As changes in task durations typically occurred gradually in most jobs, workers were asked to specify the five- or ten-year period during which the change occurred. The average times spent at each location in 1990 were provided to help the workers think about past durations. To help clarify the meaning of each task category, examples of the types of activities carried out in each category were appended to the profile. Between one and 13 interviews were carried out for most trades. Workers were generally able to repeatably recall times spent at different tasks or locations. However, for transmission linemen and mobile substation operators, where the mix of voltages could differ widely for a given task, individuals interviewed could not precisely describe the time spent near lines of different voltage levels. Because finding active workers who had started at the utility before the mid 1950s was difficult, some retired employees were contacted. This made it possible to explore from the late 1930s onwards.

2.2.2 Estimation of past exposure intensities for tasks or locations

The intensity of a utility worker's exposure to ELF fields from energized conductors depends on the current and voltage on the conductors, the number of conductors, their geometry and phasing, and the worker's proximity. The increased demand for electricity over the years has been met by the addition of transmission and distribution circuits and increases in line loading and line voltage. These increases are expected to have increased magnetic and electric field levels near the lines, but will only have translated into higher exposures today if distances between workers and sources have remained the same.

For each job category, experts from the utility and long-term workers were met to review the changes in equipment, work practices, and locations that had occurred over time. Experts were asked to judge what effect each change might have had on exposure. From meetings with utility experts, we obtained historical information on transmission line lengths, voltages and durations of maintenance work. We did not have access to historical records of line loadings, substation capacities or the numbers of substations in the past. This information would have allowed estimation of the overall increase in magnetic field levels. Shortly after completing the study, we obtained limited information on historical levels of power production that, with the historical transmission line data, were used to estimate mean loadings on transmission lines; these results are reviewed in the discussion.

Given the limited amount of historical data on the changes in the transmission and distribution network, we judged that the most reliable method to determine past exposure intensities was by extrapolating the present exposure measurements (5) to past conditions of line voltage and load current where these were known. Where this information was not available, some reasonable assumptions about field levels in the past were applied, based on the general descriptions of system changes obtained during interviews.

2.3 Reconstruction of profiles for past periods

After completing the interviews, present and past estimates of mean intensities and durations of exposures for tasks and locations were tabulated for five or 10-year intervals, to calculate a time-weighted average (TWA) for each interval. Table 3 illustrates the reconstruction for distribution linemen. Referring to the table, the data in the last column (1990) are the measured values from a sample of workers. Duration data for earlier years are from interviews, and intensity data are extrapolated from the 1990 values based on knowledge of system changes. The four task / location categories are: "low" (all tasks performed under documented low magnetic, e.g., ≤ 0.2 μT fields); "bucket" (all tasks performed from the insulated bucket); "pole" (all tasks performed while attached to the pole) and "ground" (all tasks performed while on the ground underneath or near the distribution lines). Finally, for jobs that no longer existed in 1990, past exposures were reconstructed by using exposure intensity data from comparable tasks in other jobs and multiplying by time estimates obtained from interviews. As the calculated past TWA exposures for a job category were based on a subsample of workers from the category, they were not used directly in the epidemiological study. Instead, the ratios of the TWA exposure for each past period over the TWA exposure for 1990 were used (shown in the last rows of Tables 3a and 3b). For the epidemiological study, the measured mean magnetic (or electric) field for a job category was multiplied by the ratio for each past period.

3. Results

Of the 32 job categories reviewed, 14 were judged likely to have had past exposures to either 60-Hz electric or magnetic fields substantially different from the 1990 measured values. The last columns of Table 1 shows the ratio of estimated TWA fields in 1945 to that in 1990. Among the 14 job categories, magnetic field exposures were estimated to have increased most over time for job categories working in substations and on distribution lines. Magnetic field exposures for the two jobs in the generation and transmission of electricity were estimated to have varied little over the years. For substations, the ratio of magnetic fields in the period 1945-49 to those in 1985-90 ranged from .42 to .69 for the four job categories. Of the eight jobs involved in the distribution of electricity, all but one showed increases in magnetic field levels over time, with the 1945/1990 ratios ranging from .36 to .94. For electric fields in substations, the estimated increase over time was not as steep as for magnetic fields; ratios of fields in 1945 and 1990 ranged from .59 to .88. For distribution line jobs, past electric field exposures were judged as lower than 1990 in four cases (1945-1990 ratios: .6 to .89), higher in three others (1945/1990 ratios: 1.13 to 2.01) and unchanged in one. Figures 1 and 2 show the magnetic and electric field estimates for the 14 job categories as a function of time.

Except for hydroelectric generating station operators, all of the 14 jobs are carried out in one of three work environments: transmission lines, distribution lines or substations. The changes in these environments are reviewed to illustrate how the intensities and durations of past exposures were estimated for the jobs within them.

3.1 Transmission line jobs

Of the three transmission line job categories (Table 1) only transmission linemen appeared in the list of jobs held by cases or controls of the cancer study. Tasks and work locations have changed little over time: linemen patrol, inspect and maintain high-voltage transmission lines (44 to 765 kV), maintain telecommunication towers and in the past cleared vegetation from the rights-of-way under the lines. In the past, lines were de-energized more often while maintenance work was being done. Work on energized lines (live-line) is done either with the "hot stick" method where an insulated rod is used to manipulate line hardware, or with the "contact" method, where the lineman works at arms' length or closer to the conductors. Other changes have occurred in the way patrols are done. In the past, these were by truck, jeep, horseback, by foot or on snowshoes. Now, the all-terrain vehicles, snowmobiles, and helicopters used to patrol lines are likely to have reduced the time spent in the rights-of-way. Interviewed workers were unable to clearly define the proportion of live-line work or the breakdown between hot stick and contact work. Consequently, we did not attempt to adjust for these changes in our estimates of past exposure intensities. Transmission line voltages have been steadily increasing over the years (Table 4). In 1906, Hydro-Quebec's network consisted essentially of 69 kV lines. By 1991, one third of the transmission system consisted of 735 kV lines. Between 1955 and 1991, the total length of high-voltage transmission lines increased fivefold to reach 28,218 km. Current capacity of lines has also increased, but records of line loading were not available. In summary, the factors that would have reduced linemen's magnetic and electric field exposures in the past compared to those of 1990 were lower voltages, less current on conductors and less use of the contact method.

To estimate the intensity of transmission linemen's magnetic and electric field exposures by task in the past, we separated the monitoring data by line voltage. When 60-Hz magnetic and electric fields were plotted against line voltage (Figures 3 and 4) electric fields showed a clear increase with increasing voltage level, with a less clear trend for magnetic fields. Electric fields for a given voltage line were assumed not to have changed over time. For magnetic fields, we did not have data on average line loads, or overall loading of the network. We judged that increases in the loading of the transmission line network were likely to have been offset by the addition of circuits, and thus did not adjust the estimates of magnetic field intensity.

As workers had expressed difficulty in recalling the time spent at each voltage level, we considered using the records of transmission line length and time spent inspecting, maintaining and repairing lines (Table 4) as a guide. Comparison of the time data with the total length of transmission lines showed a clear increase over the years as the total length of transmission line circuits had increased (r=.97). We judged that the total length of lines at each voltage level might serve as a good surrogate for the proportion of time workers would have spent inspecting, maintaining and repairing lines of that voltage. The proportion of time spent at each voltage level in 1991 compared with total line length and total circuit length for 1991 correlated more highly with total line length than for total circuit length (r= .88, .71). Accordingly, the total length of lines at each voltage level was used as a surrogate for the time that would have been spent inspecting, maintaining and repairing the line. Line length data were available for 1925, 1955, 1965, 1986 and 1991.

3.2 Transformer substations

Four of the six substation job categories were considered for past extrapolation (Table 1). As the 735 kV substations were new, the tasks and locations of electricians and operators in them were judged to have changed little over time. Substations typically consist of a high-voltage supply section (e.g., 300 kV) and two lower voltage output sections (e.g., 120, 12 kV). During the 1950s, 60 kV and 12 kV were the most common voltage levels. In 1990, 120 kV and 69 kV were most common, with the 69 kV substations gradually being shut down. A substation is designed to handle a certain amount of power, but reserve capacity in the circuits and equipment allows for increased loads. When these reach capacity, extra circuits and equipment are built, causing substations to expand in area over time. Expansion alone will not necessarily have increased magnetic field exposures, unless the load on individual circuits has also increased. Since conductor spacing and clearance differ for different voltage sections, upgrading to higher voltage levels may not have increased electric field exposures in proportion to the voltage level. Generally though, exposures in substations in the past were likely to have been lower than 1990 values due to lower substation loadings, and lower voltages. The lower intensities may have been offset for apparatus electricians, mobile operators and technicians, by the greater duration of time spent in the substations in the past. Maintenance workers (civil and mechanical engineering), who spent about the same amount of time in substation yards in the past, are likely to have had lower exposures.

We were unable to obtain historical data on the number and types of substations or typical substation loadings. Our estimates of substation ELF field intensities were based on the monitoring data. The electric field exposures in substation yards showed some association with substation voltage for mobile operators only (r=.34) (Figure 5). Magnetic fields, however, showed strong dependence on substation voltage for mobile operators (r=.88), but not the other jobs (Figure 6). Considering all the changes in substations over the years, and using present levels in 69 kV substations as a guide, magnetic and electric field intensities for the 1950s were estimated as one-half of the 1990 values.

3.3 Distribution lines

Except for meter readers, past exposures of all the distribution line job categories were considered as likely to have differed from present (Table 1). The results for distribution linemen, a trade that has undergone considerable change over the years, are presented here as an example of the changes that have affected distribution line jobs over time. These linemen repair and construct overhead electrical distribution lines of medium voltages (2.4 to 34.5 kV) and low voltages (750 volts and less). Before the 1970s and the arrival of bucket trucks, linemen worked in groups of five to 10, with two distinct exposure subgroups: those who worked directly with the lines from the pole (lineman, lead hand, apprentice lineman) and a less-exposed group who prepared materials or coordinated work on the ground (groundman, laborer, handyman, driver, foreman).

Today, distribution linemen work in teams of two or three people. The work is rotated, with no distinction between linemen and groundmen. Foremen are no longer on the job site, as most of their duties have been transferred to the lead hands. Consequently, foremen are exposed for less time than in the past.

Before 1960, the dominant voltage in the aerial distribution network was 4 kV, with maximum amperages typically between 200 and 300 A. In the early 1960s to the early 1970s, the 4 kV lines were gradually converted to 12 kV, with maximum amperages near 400 A. From the late 1960s onwards, lines were converted to 25 kV, with maximum amperages near 500 to 600 A. During the late 1970s, electric heating of residential buildings became increasingly popular, which lead to a large increase in the electricity being carried by distribution lines, particularly the secondary, low voltage lines (120/240 V).

With the introduction of improved materials and tools, durations of many routine tasks have decreased over time. The size of conductors has been increased to keep up with the demand for increased amounts of electricity and transformers are more numerous and larger than in the past. As lines can now be isolated in more places, more work is presently done on de-energized lines. Methods for live-line work have evolved over time. Until the early 1960s live line work up to 4 kV was carried out using rubber gloves; higher voltage lines were de-energized. Linemen would use spikes to climb poles. Once in the work zone, they would attach themselves to the pole using a belt or plank. The distribution linemen interviewed estimated that in 1945-1949 their trade spent on average 35 hours a week working from the pole (Table 3). From the early 1970s to the present, the most important change was the arrival of the bucket truck (or boom truck), which greatly reduced the need to climb poles and allowed routine tasks to be done more rapidly. In 1970 the average time spent up on the pole was estimated as 10 hours, and in 1975 as 30 minutes when the change to bucket trucks was complete. Also during this period, the quality of rubber gloves was improved to the point where lines up to 34 kV could be handled. Linemen in most regions of the utility alternated between the contact and hot stick methods, but linemen of one urban region have used the contact method almost exclusively. The contact method was found to result in higher exposures to magnetic and electric fields than the hot stick method, because the lineman's body is closer to the conductors. Overall, several factors would have made past exposures higher than the measured 1990 values. These include more work on the poles, less use of hot sticks, more time spent close to the wires, and fewer places to isolate lines. Factors that will have reduced past exposures compared with 1990 include lower voltages, less maintenance work, lower amperage on primary and secondary lines, and fewer transformers.

To derive estimates of magnetic and electric field intensities, we separated the monitoring data according to voltage level (Table 2). For work done from an insulated bucket, or for work done from the ground, the dependance of electric and magnetic field exposure on line voltage was clear. Consequently, field intensity values were used as a baseline in assigning exposures for past periods. These were adjusted upwards or downwards to reflect changes in work methods and the dominant line voltages at the time. Historical information on line loading or on line lengths at each voltage level, which would have allowed estimation of the increase in average loads on lines, were not available at the utility. In our discussions with utility managers and senior workers, most estimated that the average loadings on lines had increased by a factor of about two since the 1950s. Thus, for work on distribution lines, and in distribution cable vaults, we used one-half of the 1990 value for magnetic fields as a baseline estimate of field levels. Given the increases in distribution line currents over the years and the changes in work methods, the 1945 value for the intensity of average exposures during pole work was estimated as about 40% of the 1990 value for bucket work. We estimated ground work exposures in 1945 as about 60% of the 1990 values.

4. Discussion

In this retrospective exposure assessment, we reconstructed exposures to 60-Hz magnetic and electric fields for 14 of 32 job categories at Hydro-Quebec. Of the 18 unadjusted job categories, we excluded two job categories with high electric or magnetic field exposures (forestry workers, transmission cable splicers) because they did not appear in the list of jobs held by the cases or the controls of the epidemiological study. The past exposures for these trades may have differed from the published 1990 values. (5) The operators / dispatchers of the regional and distribution control centres (RCC/DCC) some of whom were based in substations in the past, were not considered for readjustment because job histories did not specify work sites. Similarly, for meter readers who in the past were either industrial or residential meter readers, work histories did not specify sites. The remaining job categories were not considered for readjustment because we could find no evidence of changes that were likely to have substantially altered exposures, or we expected the exposure to be low. Low exposures to ELF magnetic and electric fields were expected for the office-workers, blue-collar workers in buildings not located near generation transmission or distribution facilities, estimators and instructors. We judged that adjustment of an already low exposure would not have substantially changed the results of the epidemiological study, and consequently excluded these jobs.

We designed this retrospective exposure assessment to reduce the subjectivity of past exposure estimation. This was achieved by basing estimation on measured durations and intensities of task exposures from randomly selected workers, and by restricting subjective opinion largely to the estimation of past task durations. The validity of the past exposure estimates cannot be directly verified, as no historical exposure measurements are available with which to compare. Dosemici has described a method for indirectly validating retrospective exposure estimates (10) but it requires that the exposure be a risk factor for cancer, which remains unclear for ELF fields.

The estimates of past TWA exposures derived here will have been most sensitive to past task estimates in which the products of intensity and duration dominated the TWA exposure. Systematic documentation of line loadings and substation types would improve our confidence in these estimates at the utility. Due to time constraints, we interviewed but a few engineering and system-control head-office personnel. The lack of records of system changes over time limited our ability to estimate the past intensities of magnetic and electric fields for substations and distribution lines. However, after completing the reconstruction process we obtained partial historical information on power generated by the utility that, with the data described previously, allowed an approximation of the average historical loading on transmission lines. To re estimate how magnetic fields might have changed over time as current loading on transmission lines has increased, we estimated average current loads for 1954, and for 1990 based on the model:

$$\bar{I} \cong P * (n\bar{V})^{-1}$$

where $\bar{I}$ is the mean current, P is the power generated, n is the number of circuits, and $\bar{V}$ is the weighted mean transmission line voltage (weighted by length of line at each voltage). Here, n is approximated by the total circuit length of the transmission line network. Over the 1954 to 1990 period, weighted mean line voltage increased by a factor of 2.5 (141 kV to 350 kV), total circuit length increased by a factor of 5.4 (6374 km to 34193 km) and power generated increased by a factor of 14.4 (8000 M KWH to 115,000 M KWH). The increase in circuit length offset the increases in generated power and voltage, and yielded a ratio of mean currents in 1990 over 1954 of 1.08. This provided support for our decision not to reduce past magnetic field intensities for transmission linemen.

Our estimates of historical exposure intensities in substations and near distribution lines could not be verified in this way, as supplemental data were not available. However, comparison with the results from Ontario Hydro (OH) where historical data on transformer loadings in 1950 and 1990 were available (11) can provide some insights. Over this period, overall loading on OH substations was estimated to have increased by a factor of 4.6, while total energy divided by the number of stations had increased by a factor of 2.7. The average (3.7) of these two factors was thus used as an estimate of the average increase in magnetic fields in OH substations. Over that period, power generated in Ontario had increased by a factor of 9.1 (from 15,900 M KWH to 145,000 M KWH). At Electricite de France, the square-root of power consumption was used as an approximation of the increase in magnetic field levels over time.(12) Applying this to the OH data yields an estimated threefold increase in magnetic fields; applying it to the 19-fold increase in the amount power generated in Quebec between 1950 and 1990 (5,922 M KWH to 115,000 M KWH), suggests an approximate fourfold increase in Hydro-Quebec's substation magnetic fields. Thus, our estimate of a twofold increase in substation magnetic fields may have been conservative. For electric fields our estimate of a twofold increase between 1950 and 1990 is identical to that of Ontario Hydro.

5. Conclusion

This method of retrospective estimation of ELF-EMF exposures possesses several advantages. It allows separate estimation of the effects of changes to the duration and intensity of exposures. It relies on measured durations of time spent at tasks and work locations, and measured exposure intensities. Further, interviewed workers are only required to comment on the past durations of tasks. The main limitations in this application of the method were small sample sizes and poor documentation of system changes at the utility. The method described here can apply to contexts other than electrical utilities, if exposure intensities are measured at the level of tasks, and the durations of tasks are estimated. Extrapolating exposures for tasks is simpler than for jobs, as the complexity of dealing with task durations is removed to be dealt with separately. Finally, a simple modification of the method described here, in which workers keep logs of the durations of tasks they perform over several weeks, can improve the accuracy of long-term exposure estimates. (13)

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Table 1 Historical changes identified for job categories

Job category	Key past differences identified during interviews	Past exposures likely to have differed substantially from 1990 values	Number of worker-records analyzed	Ratio of 60-Hz fields 1945/1990	
				Magnetic	Electric
Expected low exposure jobs					
Blue collar jobs*	Expected low exposure	No			
White collar jobs*	Expected low exposure	No			
Hydroelectric generation					
Equipment electricians	Minor changes in sources & tasks	No			
Equipment mechanics	" "	No			
Foreman, operations and others	" "	No			
Operator, hydro generating station	Job titles and functions different in past	Yes	8	1.1	1.03
Nuclear generation					
Equipment electricians	No changes since inception in 1983	No			
Operator, nuclear station	" "	No			
Diesel generation					
Operator, autononous network	No changes since inception	No			
Transmission					
Forestry worker	No cases or controls	Not considered			
Transmission splicer	"	Not considered			
Transmission lineman</= 735 kV	Less "contact" work; lower voltages; more time in right of way	Yes	9	1.05	0.84
Substation					
Equipment electrician </=735 kV	Lower amperages & voltages; more time in substation	Yes	11	0.55	0.69
Equipment electrician 735 kV subst	No changes since inception of this type of station	No			
Maint. worker, civil & mech. engin.	Lower amperages & voltages	Yes	6	0.42	0.59
Operator, mobile	Lower amperages & voltages; more time in substation	Yes	13	0.53	0.88
Operator, 735kV substation	No changes since inception of this type of station	No			
Technician, automatic control/relay	Lower amperages & voltages; more time in substation	Yes	9	0.69	0.74

(Continued)

Table 1 (cont) Historical changes identified for job categories

Job category	Key past differences identified during interviews	Past exposures likely to have differed substantially from 1990 values	Number of worker-records analyzed	Ratio of 60-Hz fields 1945/1990	
				Magnetic	Electric
Distribution					
Emergency man	Lower voltage and current; recent job, limited to 2 regions	Yes	5	0.36	0.60
Foreman, OH lines	Lower voltage and current; more time in field in past	Yes	§	0.92	2.01
Foreman, UG lines	Lower voltage and current; more time in field in past	Yes	§	1.03	0.82
Lineman, contact & hotstick method	Lower voltage and current; more time on poles in past	Yes	22	0.94	1.68
Lineman, contact method	Lower voltage and current; more time on poles in past	Yes	15	0.82	1.13
Meter installer	Lower voltage and current; some time on poles in past	Yes	5	0.47	1.00
Meter reader	Industrial and residential meter readers separate jobs in past; but unable to differentiate from work histories	No			
Splicer, distribution	Lower voltage and current; more time in cable vault in past	Yes	15	0.74	0.89
Tree trimmer	Now subcontracted	Yes	5	0.49	0.68
Others					
Estimator	Less office work in past, but low exposure	No			
Instructor	Two groups in past (substations, others), but low exposure	No			
Licensed electricians	Minor changes in sources & tasks	No			
Operator/dispatcher RCC/DCC¶	Formerly in substations, but unable to differentiate from work histories	No			
Technician, telecommunications	No changes in sources & tasks, and recent job category	No			

¥ blue collar jobs:

Clerk, accounting / judicial / mail / stores / data entry
Meter inspector, Storekeeper
Mechanic, vehicles and equipment
Toolkeeper
Technician, planning/ management

¤ white collar jobs:

Agent, Division head, Section head, Shift supervisor
Consultant, systems management / personnel
Engineer
Commercial representative

¶ Regional control centre, distribution control centre
§ Reconstructed from task exposures for linemen

Table 2a Task and location exposure estimates for Hydro-Québec distribution linemen (contact method)[¥]

Task name	No. of meas.	Total dur. (min)	Electric (V/m)		Magnetic (uT)	
			AM wgt[¶].	(95% C.I.)[§]	AM wgt.	(95% C.I.)
1 Expected low-exposure work[*]	110	6350	3.62	(2.34, 5.60)	0.18	(0.15, 0.21)
2 *Work done from bucket*						
Voltage not stated	2	152	1289.67	(-.- -.-)	27.81	(0.00,8.05E+10)
Secondaries, < 600 V (hookups)	17	1425	88.20	(35.64, 218.27)	2.96	(1.37, 6.41)
Construction (dead-line, live-line)	16	1855	252.15	(47.76, 1331.20)	0.56	(0.37,0.86)
Primaries, 12 kV (gloves)	17	2135	418.26	(61.01, 2867.22)	2.48	(0.77, 8.02)
Primaries, 25 kV (gloves)	10	974	1817.89	(335.61, 9846.87)	3.84	(0.99,14.85)
3 Work done from pole	2	141	196.03	(84.68, 453.78)	0.25	(0.09, 0.75)
4 *Work on ground*						
Groundman work (voltage not stated)	24	1862	8.89	(4.57, 17.32)	0.29	(0.20, 0.43)
Groundman work (under 12 kV lines)	3	208	13.93	(0.41, 469.23)	0.39	(0.32, 0.47)
Groundman work (under 25 kV lines)	10	810	42.53	(8.37, 216.15)	0.62	(0.31, 1.27)
Total exposure	211	15912	223.58	(98.96, 505.11)	1.31	(1.02, 1.67)

[¥] Based on 15 workers sampled in July and August 1989.

[*] Includes office, garage, storeroom, transportations, meals and coffee breaks.

[§] Arithmetic mean weighted by duration of each task

[¥] Cox approximation for unweighted arithmetic mean

Table 2b Task and location exposure estimates for Hydro-Québec distribution linemen (contact method), all voltage levels combined

Task name	No. of meas.	Total dur. (min.)	Electric (V/m) AM wgt.	Electric (V/m) 95% C.I.	Magnetic (uT) AM wgt.	Magnetic (uT) 95% C.I.
1 Expected low-exposure work	110	6350	3.62	(2.34, 5.60)	0.18	(0.15, 0.21)
2 Work done from bucket	61	6391	540.04	(186.57, 1563.22)	2.89	(1.74, 4.80)
3 Work done from pole	3	291	100.65	(2.98, 3404.44)	0.25	(0.14, 0.44)
4 Work on ground	37	2880	18.72	(9.89, 35.41)	0.39	(0.28, 0.54)
Total exposure	211	15912	223.58	(98.96, 505.11)	1.31	(1.02, 1.67)

Table 3a **Calculation of 60-Hz magnetic field correction factors for distribution linemen (contact method)**

(Magnetic fields in microtesla)

Task/location	1940 - 1949		1950 - 1959		1960 - 1964		1965 - 1969		1970 - 1974		1975 -1989		1990	
	h/wk	mag (µT)	h/wk	mag (µT)	h/wk	mag (µT)	h/wk	mag (µT)	h/wk	mag (µT)	h/wk	mag (µT)	h/wk	mag (µT)
Low	10	0.13	10	0.13	10	0.14	10	0.15	16.5	0.16	18	0.18	18	0.2
Bucket	0		0		0		0		7	2.89	13.5	2.89	13.5	2.89
Pole	35	1.25	31	1.25	27.5	1.5	27.5	1.75	10	2	0.5	0.25	0.5	0.25
Ground	5	0.24	5	0.24	5.5	0.28	5.5	0.32	8.5	0.36	8.5	0.39	8.5	0.39
Total h/wk	50		46		43		43		42		40.5		40.5	
TWA (µT)	0.93		0.90		1.03		1.20		1.09		1.13		1.13	
Correction factor	0.82		0.79		0.91		1.06		0.97		1.00		1.00	

Table 3b Calculation of 60-Hz electric field correction factors for distribution linemen (contact method)

(Electric fields in volts per metre)

Task/location	1940 - 1949		1950 - 1959		1960 - 1964		1965 -1969		1970 - 1974		1975 - 1989		1990	
	h/wk	elec. (V/m)	h/wk	elec (V/m)	h/wk	elec (V/m)	h/wk	elec (V/m)	h/wk	elec (V/m)	h/wk	elec (V/m)	h/wk	elec (V/m)
Low	10	3.6	10	3.6	10	3.6	10	3.6	16.5	3.6	18	3.6	18	3.6
Bucket	0		0		0		0		7	450	13.5	540	13.5	540
Pole	35	300	31	300	27.5	300	27.5	300	10	400	0.5	101	0.5	101
Ground	5	10	5	10	5.5	10	5.5	10	8.5	15	8.5	19	8.5	19
Total h/wk	50		46		43		43		42		40.5		40.5	
TWA (V/m)	212		204		194		194		175		187		187	
Correction factor	1.13		1.09		1.04		1.04		0.93		1.00		1.00	

Table 4 Growth of electrical transmission lines in Québec

	Km of transmission lines Voltage (kV)								
Year	44	69	120	161	230	300	735	Total line length	Total person-years of inspection, maintenance & repair
1906	0	53	0	0	0	0	0	53	1.04
1911	0	54	37	0	0	0	0	91	1.29
1917	48	188	48	0	0	0	0	284	3.92
1925	100	231	48	0	108	0	0	487	5.79
1955	589	947	2,165	404	1,241	282	0	5,628	46.33
1965	591	2,093	3,184	712	2,004	2,042	640	11,266	79.24
1986	656	2,880	5,853	1,504	3,038	3,796	10,175	27,902	176.27
1991	656	2,904	5,998	1,584	3,042	3,859	10,175	28,218	240.44

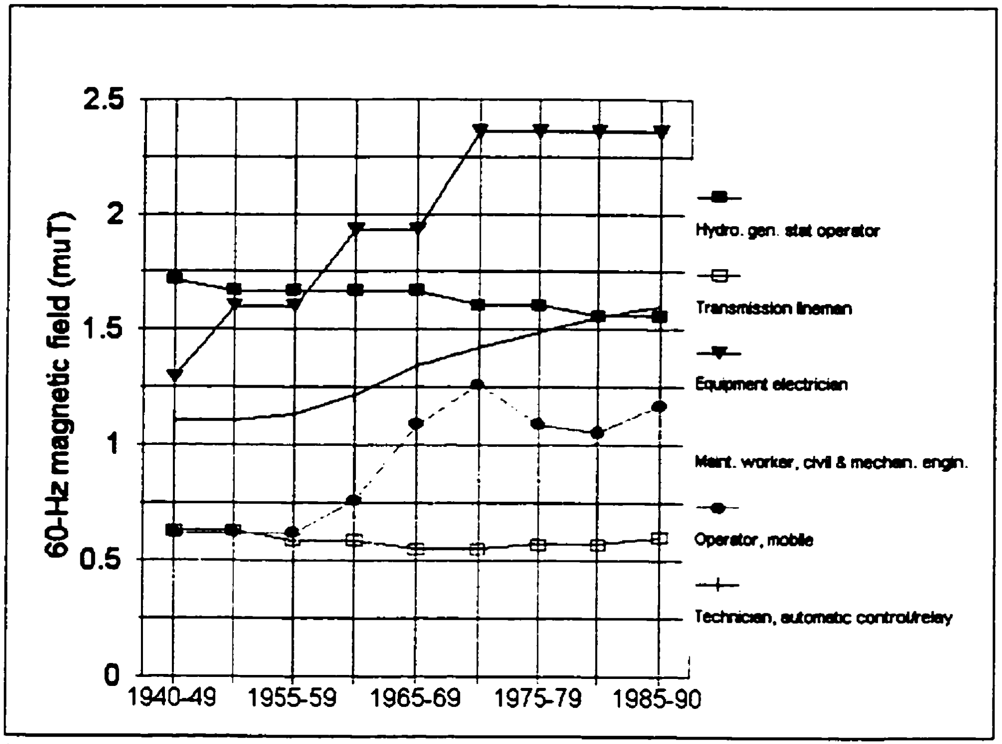


Figure 1a. Estimated past exposures to 60-Hz magnetic fields at Hydro-Quebec: Generation, transmission and substation jobs

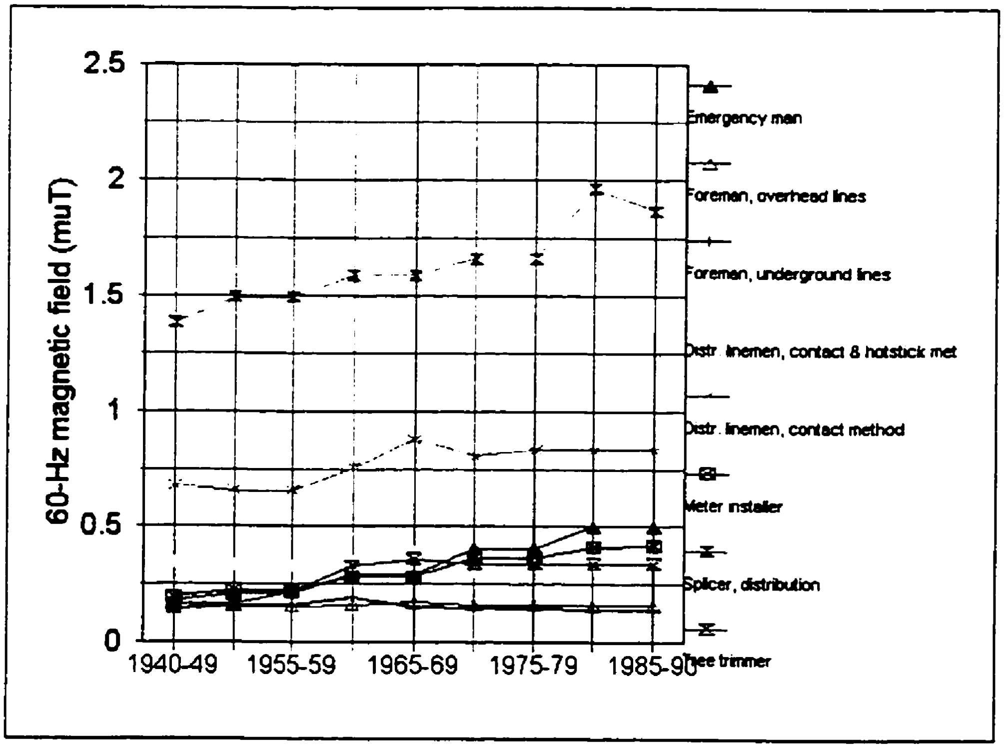


Figure 1b. Estimated past exposures to 60-Hz magnetic fields at Hydro-Quebec: Distribution jobs

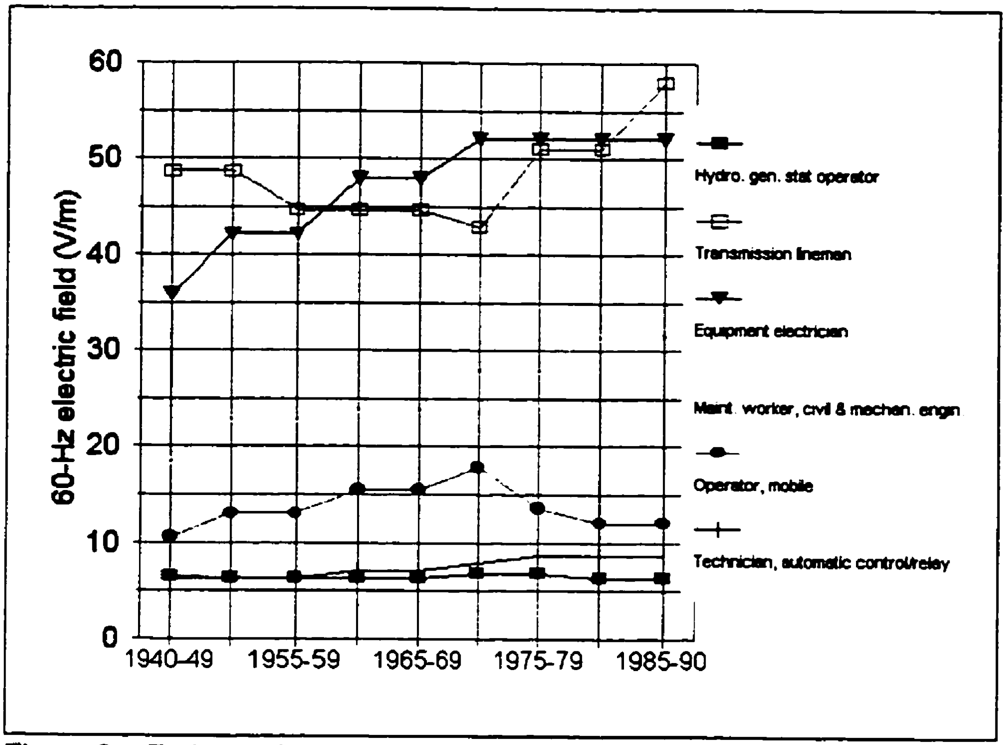


Figure 2a. Estimated past exposures to 60-Hz electric fields at Hydro-Quebec: Generation, transmission and substation jobs

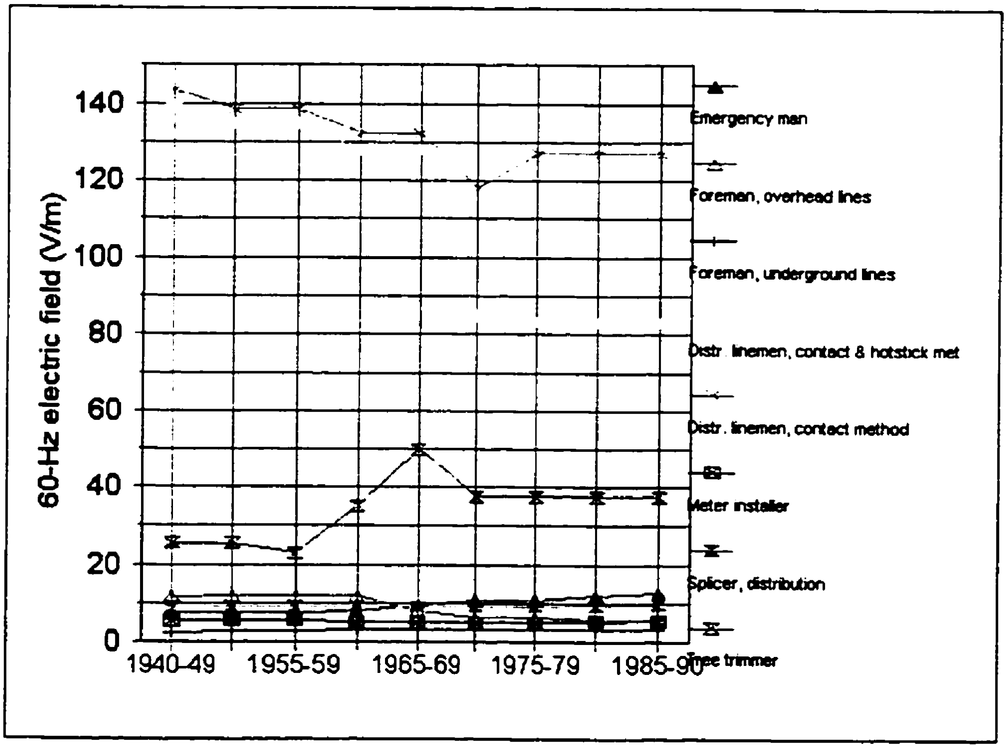


Figure 2b. Estimated past exposures to 60-Hz electric fields at Hydro-Quebec: Distribution jobs

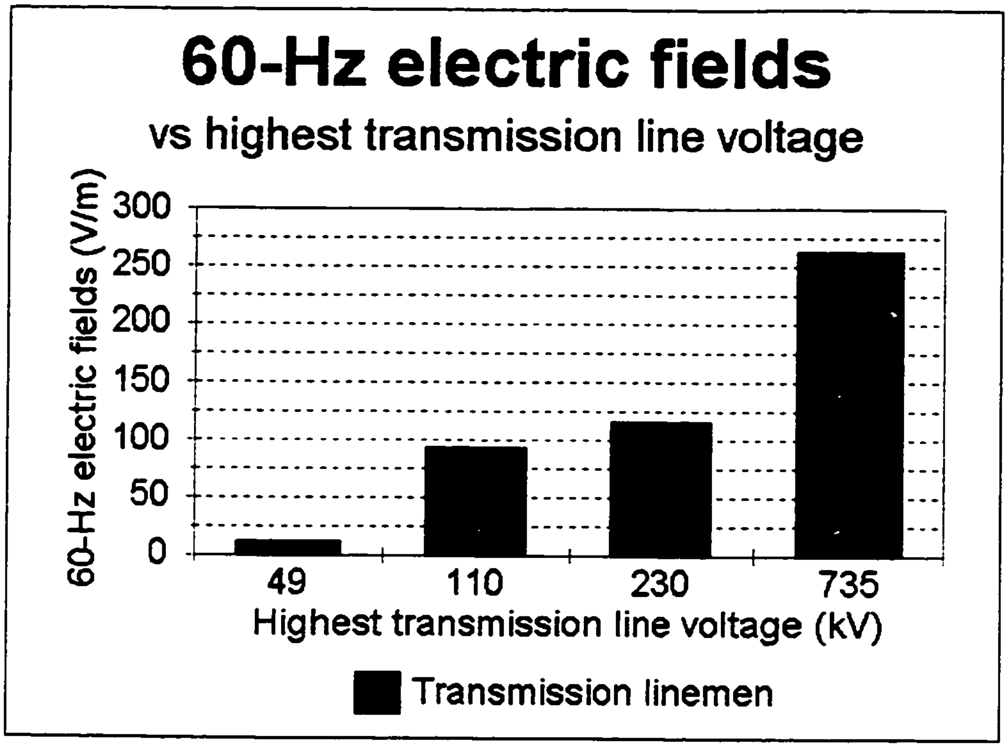


Figure 3

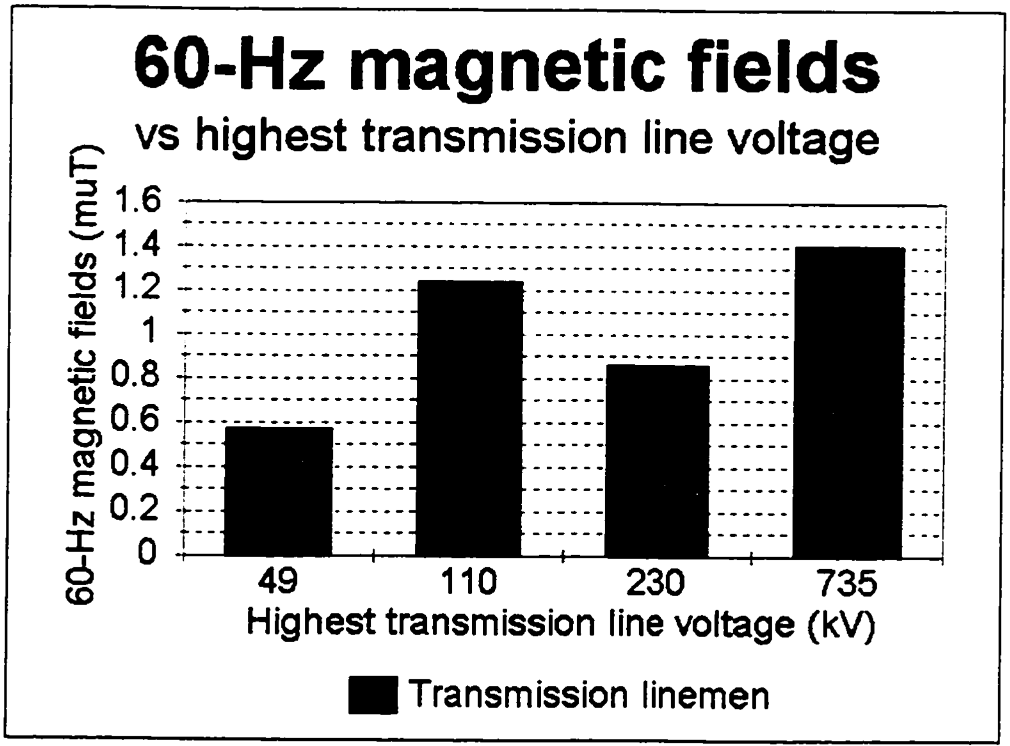
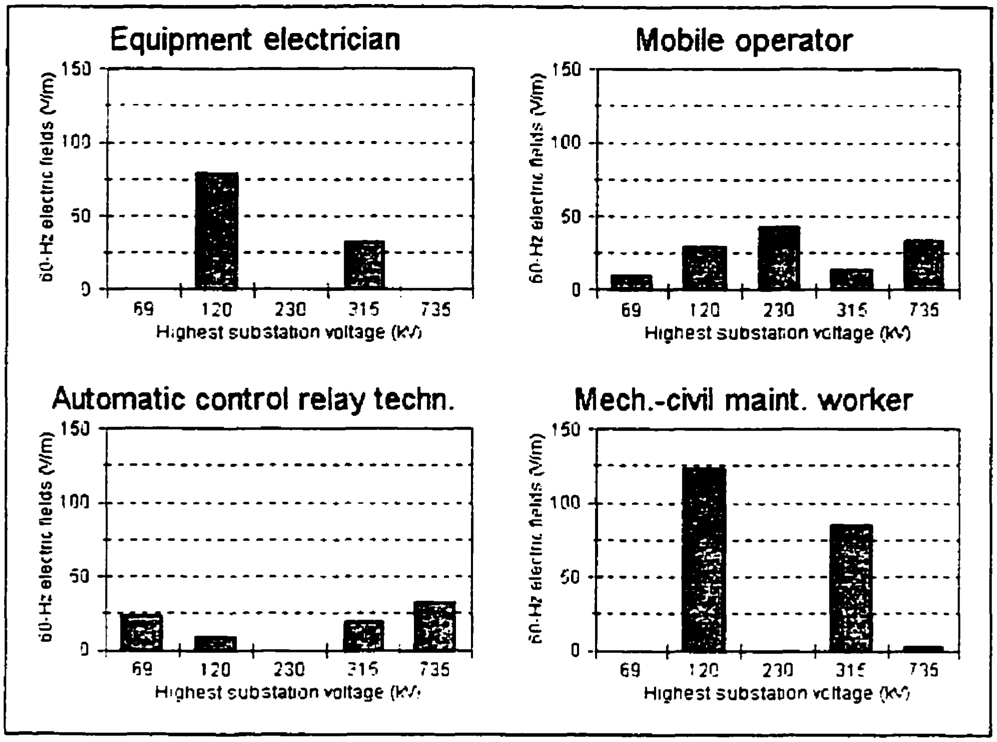


Figure 4

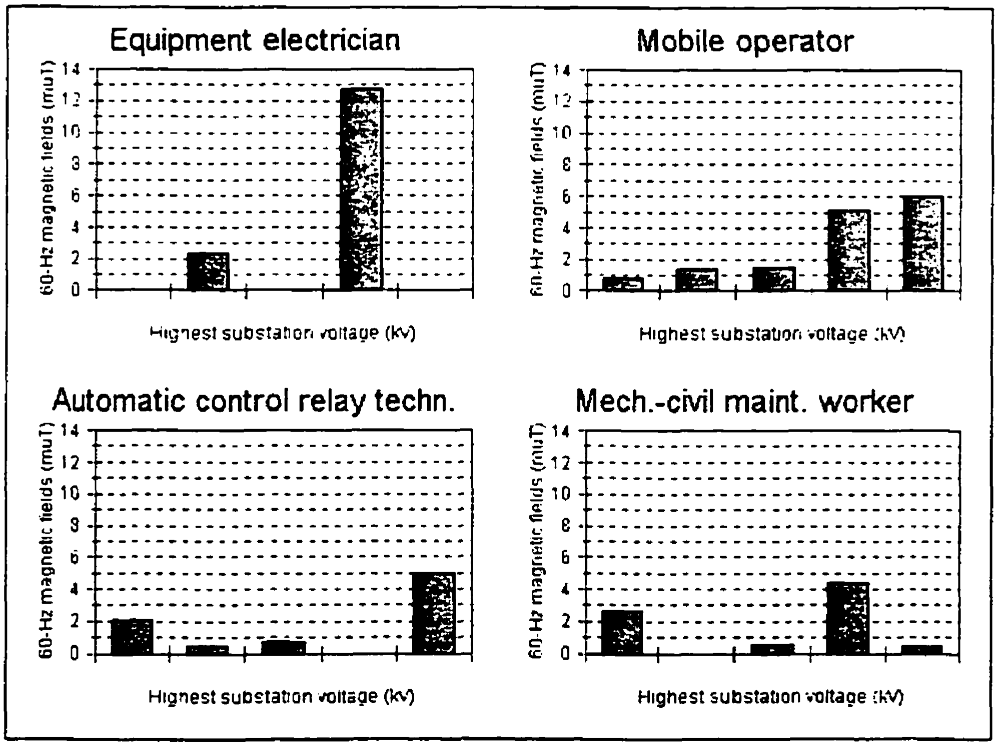

Equipment electrician

Mobile operator

Automatic control relay techn.

Mech.-civil maint. worker

Figure 5 60-Hz electric fields vs highest substation voltage


Equipment electrician

Mobile operator

Automatic control relay techn.

Mech.-civil maint. worker

Figure 6 60-Hz magnetic fields vs highest substation voltage

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5. Exposures of children in Canada to 60-Hz magnetic and electric fields

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Abstract

Objectives To characterize exposures of Canadian children to 60-Hz magnetic and electric fields and explain the variability of exposures.

Methods For a prospective case-control study of childhood cancer, 365 control children 15y of age or younger in five Canadian provinces wore meters that recorded 60-Hz magnetic and electric fields over two days. During sleep, meters were under the child's bed. An adult or the child kept a diary of activities. On a third day, meters were left to record fields in the centre of the child's bedroom for 24 h. Exposures were calculated for home, school or daycare, outside the home, bedroom at night, and for all activity categories combined (total).

Results The arithmetic mean of total magnetic fields was 0.121 μT (GM: 0.085, min. 0.01, max. 0.8 μT). Fifteen percent of total exposures exceeded a level of 0.2 μT. The arithmetic mean of total electric fields was 14.4 V/m (GM 12.3, min. 0.82, max. 64.7 V/m). By activity category, the highest magnetic field exposures were at home during the day (.142 μT); the lowest during the night (.112 μT). Measurements during sleep provided the highest correlation with total magnetic field exposure (r= .91). Province explained 14.7% of variation in logarithms of total magnetic fields, season an additional 1.5%. Electric heating, air conditioning and housing type appeared to be useful predictors of magnetic field exposures.

Conclusions This study has identified differences in children's magnetic field exposures between provinces that appeared to depend largely on the extent to which homes were heated by electricity and cooled by air conditioning. The roles of wiring type, type of housing and outdoor temperature in predicting magnetic field levels require further investigation. For prediction of total magnetic field exposure, measurements at night provided the best surrogate, followed by the at-home exposures and the 24-h bedroom measurements.

1. Introduction

Since Wertheimer and Leeper (1) first associated childhood cancer with power line wire codes, a surrogate for magnetic fields inside residences, some studies have linked childhood leukemia with wire codes (2)(3) or with historically extrapolated magnetic fields (4) while others have not. (5)(6)(7)(8)(9) In the studies that followed Wertheimer and Leeper's work, researchers have sought to improve exposure assessments by including daytime spot measurements of magnetic fields at the front doors of residences (7), daytime spot measurements of magnetic fields inside subjects' homes under high and low power conditions (2,3)—the latter intended to evaluate the persistent fields from outside power lines— 24-hour measurements in the child's bedroom (3) and residential spot measurements corrected for past loadings on nearby power transmission lines. (4)

For a prospective case-control study in Canada designed to examine the possible association between 60-Hz electric and magnetic fields (ELF-EMF) and subsequent risk of childhood leukemia, we measured personal exposures of cases and controls to 60-Hz magnetic and electric fields. These measurements were part of a broader exposure assessment protocol that included wire coding of subjects' residences, daytime spot measurements of EMF magnetic fields around the perimeter of residences, and collection of information on electric blanket and electric heating use and type of housing. Results of the broader exposure assessment will be reported separately. This paper reports on the personal exposure measurements of 382 control children of ages less than 15y. We examine the distribution of exposures in five Canadian provinces, the variability of exposures between provinces, between seasons, between days of the week and between activity categories inside and outside of the home. The roles of electric heating, air conditioning and residence in a multiple dwelling building are explored on a preliminary basis. The exposure assessment described here improves on previous work by including: a/ monitoring of personal exposures over two days, to capture exposures that reflected each child's pattern of behaviour; b/ monitoring of perturbed electric field exposures on each child, and; c/ monitoring of magnetic field exposures during the night. Previous studies have generally not assessed electric field exposures. In those that have, electric fields have not been found to correlate with wire codes (2) or with magnetic fields (10). As ELF electric fields are capable of inducing current in the body, measurement of exposure to them is relevant if induced current is a biologically important variable. Previous studies have not assessed sleep exposures as a separate entity, yet evidence from animal studies suggests that exposures to ELF magnetic fields at night might suppress human nighttime melatonin synthesis. (11)

2. Methods

Between 1990 and 1995, 382 control children were recruited from 525 contactable controls in seven areas of the Canadian provinces of British Columbia, Alberta, Saskatchewan, Manitoba and Quebec. Control children were identified exclusively from provincial health insurance rolls for all provinces except Québec where family allowance files were also used. Children were matched to leukemia cases for gender, age and residency within the same province at the diagnosis date of the case. The data presented here include 22 controls who were ineligible for the epidemiological study because they had not lived in their current homes for more than six months. Among the

143 potential controls who did not participate, we assessed 91 homes using the Wertheimer-Leeper method of coding nearby power line wires.

Children wore Positron exposure meters (model 378108) over two consecutive 24-h periods. Children older than 8y wore meters in a waist pouch; younger children wore meters in an animal-theme backpack. For children too young to wear a meter (less than 18 months) a parent kept the meter near the child. Parents were instructed to note in a location diary the time and location every time the child changed locations, which were identified as the child's bedroom, other room, school or daycare, or other location outside the home. Parents were asked to note if the child was wearing the meter at the specified location. Children were encouraged to wear meters during all activities, where possible, inside and outside the home. To monitor exposures during sleep, the meter was placed in the child's current bedroom under the bed and at least one metre away from any visible source of electric or magnetic fields. During a third 24-h period, the meter was placed in the centre of the bedroom in which the child had slept two years prior to the date of diagnosis of the case, if that bedroom was in the current residence. If not, then the meter was left in the same bedroom as the nighttime measurements. (Measurements of exterior temperature at the time of measurements were obtained from Environment Canada for the monitoring station closest to the regions in which measurements were made, but these data were not available for this report.)

Every 60 s, the meter measured the magnetic flux density of the three orthogonal components of the 60-Hz magnetic field, and the perturbed 60-Hz electric field perpendicular to the body surface while the meter was worn. This meter was designed to exclude measurement of harmonics (frequency response at 40 hertz: -9 dB; at 400 hertz: -28 dB). Each reading was classified by the meter into one of 16 magnetic or 16 electric logarithmically scaled exposure categories. Detailed operation and characteristics of the meter have been described previously. (12)(13) For this study, primary calibration of magnetic field response was performed before and during the study, using a Helmholtz coil arrangement to determine the threshold field levels for lower bin edges of the three orthogonal field directions. An error of up to 10% difference between the threshold field values and design specifications for bin edges was tolerated. Primary calibration of electric field response was performed using two parallel plates to generate a uniform field region of known magnitude. (14) No drift of meter response was detected between calibrations. Fourty-two meters were employed in the study and were distributed at random among the study subjects. Analysis of magnetic and electric field exposures by meter revealed no differences beyond those attributable to chance.

2.1 Data analysis

On completion of the personal and bedroom monitoring, data stored in the meters were transferred to computer where the resultant (root-mean-squared) magnetic fields were calculated by Positron meter software, and data were displayed on screen as a chronological trace. From the traces, patterns of exposure were visually checked for consistency with times and activities recorded in the location diaries. Where start times recorded on the diaries and on the exposure trace differed by more than five minutes, the displayed start time was reset through the software. As electric fields are easily perturbed by body motion, their patterns served to indicate whether a meter was stationary or worn by the child. A data analyst reviewed the location diary and the exposure data of each child to identify all periods corresponding to one of five activity categories: worn-at-home, at-home-not-worn, worn-at-school, worn-outside the home (indoors & outdoors), and sleep (not worn), for each day of measurement. For each period within each activity category, meter software was used to generate an intermediate histogram file consisting of the number of readings in each of the 16 magnetic and 16 electric field bins. When a meter had been removed by a child for more than 5 minutes, these readings were excluded from the calculations of the daily means, to avoid mixing perturbed and unperturbed electric field data, the latter considered as unrepresentative of personal exposure. Each intermediate histogram was saved and classified into one of the five activity categories. For each 24-h period and for the 48-h period, intermediate histograms for each activity category were summed to a final histogram, using meter software. From the final histograms, arithmetic means and durations of the worn-at-home, the at-home-not-worn, the worn-at-school, the worn-outside, and the sleep categories were entered into a database. Finally, the total exposure of each child was calculated as the time-weighted average of measurements in all categories over the 48-h period. Correlations of exposures were examined in two ways: between the means of days 1 and the means of days 2, and between the means for the five activity categories for days 1 and 2 combined. Electric field readings during the night and other periods when the meter was not worn were not included in the total 48-h exposure, as the meter had recorded only one component (usually the vertical) of the free electric field. Due to the perturbation of the electric field by the body, personal measurements were not expected to correlate well with measurements of the free (unperturbed) electric field along a single axis made while the meter was not worn. This was confirmed by the data, which showed very low correlations of electric field exposures over 48-h while wearing and while not wearing the meter (r=.11). By comparison, the same components for magnetic fields were correlated at r=.41.

3. Results

Personal exposures to 60-Hz electric and magnetic fields were monitored over two consecutive 24-h periods for 365 of the 382 control children. For 373 of the control children, exposures were monitored in the bedrooms over an additional 24-h period. During the personal monitoring children spent 41% of their time sleeping, 30% at home, 18% at school or daycare and 11% outside the home (Table 1). Figure 1 shows that the distribution of the controls' total exposure to magnetic fields (home, school, outside and sleep combined) is skewed, with arithmetic and geometric means of 0.121 µT and 0.085 µT (GSD: 2.25). Minimum and maximum individual total 48-h exposures were 0.01 and 0.8 µT and levels of 0.2, 0.3, 0.4 and 0.5 µT were exceeded respectively by 14.5, 7.9, 3.8, and 2.1% of the 365 total 48-h exposures. By province, total exposures were greater than 0.2 µT in 21.4% of measurements in Quebec, 17.4% in Manitoba, 12.1% in BC, 1.6% in Alberta, and none in Saskatchewan. For electric fields, which also showed a skewed distribution (Figure 2), the arithmetic mean of 358 total exposure measurements over 48-hours (excluding sleep) was 14.4 V/m, the geometric mean was 12.3 V/m (GSD: 1.77), minimum and maximum values were 0.82 and 64.7 V/m. Levels of 20, 25, 30, and 35 V/m were exceeded respectively by 18.3, 8.2, 5.4, and 3% of the 358 total 48-h exposures. When magnetic fields were examined by province and activity (Table 2) the control children as a group were exposed most highly at home during the day (.141 µT) with the lowest exposures recorded at home during the night (.112 µT).

Children in Quebec generally received the highest levels of magnetic fields whether at home (0.190 µT) outside the home (.155 µT) or during sleep (.145 µT). By activity, exposures in this province were two to three times higher than those of children in Alberta, where exposures were the lowest. Total exposure to electric fields (Table 3), which excluded sleep, varied very little by province when at home or at school. Outside the home, exposures in Quebec and British Columbia were 1.6 to 1.8 times those of the other provinces. Activities at home appeared to produce the highest exposures (16.6 V/m for all controls), and school the lowest (9.3 V/m for all controls). Measurements during sleep should be interpreted cautiously because the meters only monitored a single axis of the unperturbed field. The 24-h bedroom measurements of magnetic fields (Table 4) were very similar to those during sleep on the two previous days, whether examined by province or overall. Overall, the geometric mean of the 373 24-h bedroom measurements was 0.062 µT (GSD: 2.94).

3.1 Comparison of exposures by season

To examine the effect of outdoor temperature on magnetic field levels, the data were classified by season (summer =April to October; winter = November to March). Mean exposures across the five provinces were higher during winter (0.137 µT) (95%CI: 0.114, 0.160 µT) than during summer (0.109 µT) (95%CI: 0.096, 0.123 µT). Although none of the seasonal differences were statistically significant within the provinces (Figure 3) whether examining log-transformed or untransformed exposures, winter magnetic fields showed the largest departures from summer levels in Quebec, smaller differences for BC and Alberta and lower levels than in summer for Saskatchewan and Manitoba. Electric fields (Figure 4) showed the reverse pattern from magnetic, but again none of the seasonal differences were statistically significant. When magnetic fields were plotted by month the most clearly discernable pattern was for Quebec where exposures decreased from January to May, then increased from August to January (Figure 5). Electric field exposures showed a pattern of variation opposite to magnetic but the trend was less clear (Figure 6). Monthly results in British Columbia suggested an increase in magnetic fields for the August to December period followed by lower exposures for the rest of the year (not shown). Magnetic or electric field exposures in Alberta did not show any clear trends, and numbers in Saskatchewan and Manitoba were small (not shown).

3.2 Comparison of magnetic and electric field between days

Measurements made on the two consecutive days were compared by calculating correlations between the arithmetic means of identical activities (Table 5). Magnetic fields were most highly correlated between days for school/daycare measurements (r=.85) and most weakly correlated while outside the home (r=.38). Electric fields showed a pattern similar to magnetic but correlations were lower overall. Between the two consecutive days of measurement, the median estimated between-day geometric standard deviation was 1.2 for magnetic fields and 1.3 for electric fields, compared to the between-child GSD of 2.25 and 1.77 for magnetic and electric fields, respectively. Comparison of magnetic field levels on weekends and on weekdays within the 48-h total exposure data or within the 24-h bedroom measurement data showed no consistent pattern nor any differences beyond those attributable to chance.

3.3 Comparison of the independent effects of province, season and day of week

When province, season and day of the week were entered into a regression model, province explained 8.3% (adjusted R-squared) of the variation in total 48-h magnetic fields. Addition of season improved the adjusted R-squared marginally (9.7%), but not day of the week. Patterns for each variable were not substantially altered when adjusted for the others. Using logarithms of the total 48-h magnetic field, province explained 14.7% of the variation; addition of season and day increased adjusted R-squared to 16.2% and 16.5% respectively. For electric fields, province, season and day of the week together explained only 2.3% of the variation in total 48-h exposures. Use of logarithms did not improve the fit of the model.

3.4 Comparisons of measurements between activity categories

Table 6 illustrates how exposures in the five activity category categories relate to each other and to total 48-h exposure. For magnetic fields, the highest correlation with total exposure was found for the sleep measurements (r=.91). Exposures at home during the day while the meter was worn correlated well with total exposure (r=.74), but not as highly as the sleep values. Correlation of total exposure with the 24-hr bedroom measurements was slightly lower (r=.68) than the worn-at-home value. When using logarithms, the sleep, the worn-at-home, and the 24-hr bedroom measurements all provided similar and high correlations with total exposure (r=.87, .84, .88, respectively). Within the home, the highest correlations were found between the worn-at-home measurements and those taken in the bedroom at night (r=.57) or in the bedroom over 24-h (r=.57). Exposures outside of the home did not relate well to those inside: correlations were low between the worn-at-home and the outside measurements (r=.32), and negligible between home and school / daycare measurements (r=.02). For electric fields, the highest correlation with total exposure (which excluded measurements during sleep) was found for the worn-at-home measurements (r=.76). School / daycare and outside exposures also correlated well with total exposure (r=.72, .61). At-home exposure and outside exposure correlated more highly than for magnetic fields, with r=.36 for home-school/daycare, and r=.17 for home-outside. Lastly, comparing magnetic with electric fields, the total 48-h exposures were not correlated (r=.04), but the at-home, school and outside components showed small to negligible correlations: r=.28, .17, .02, respectively.

4. Discussion

This is first report of personal measurements of ELF fields on a large sample of children selected at random from the general population, and the first in Canada. Comparison of these results with values from studies where a comparable magnetic field measurement was available (Table 10) shows that the range of results found for five Canadian provinces are similar to those reported for the United States. Our finding that magnetic fields tended to be higher in winter than in summer is supported by the results for Northern California and Maryland. In comparing these results with other studies, one must be aware that the narrow-bandwidth meter used here (Positron) is expected to yield slightly lower values than a broadband instrument (e.g., EMDEX) when harmonics are present in the field being measured. This difference is likely to be negligible, however, compared with magnetic field differences caused by the diverse configurations of electrical transmission and distribution wiring in the regions compared, by housing attributes such as the extent of electrical heating, and by season, as the data in the table would suggest.

4.1 Representativity of the results

The group of children whose exposures are reported were selected from a larger sample of 525 randomly chosen control children. To investigate how representative the results for the 365 control children were with respect to all the contactable controls, we had assessed wire-codes among a sample of 91 non-participating control homes, since wire codes are known to be associated with magnetic field levels. (The results for wire codes will be described in more detail elsewhere). Table 7 shows that, apart from the underground category, magnetic field levels increase as one moves from the lowest to the highest presumed exposure category of the Wertheimer-Leeper code. The largest increase in magnetic fields is between the OLCC and OHCC categories (.066 μT). Comparison of the wire codes among the non-participants and the participants (Table 8) showed that non-participants were more likely to have lived in a home in the VHCC category than children who did participate (Pearson Chi-Square: 10.62, p =.03). If the two categories of "high" wire codes are combined (OHCC, VHCC), however, the difference in proportions between the participants and non-participants becomes small (2.9%). As magnetic field exposures were highest in the OHCC and VHCC homes (Table 7), our sample is likely to have slightly underestimated the levels of ELF magnetic fields in children's homes in the general population. Note that the values reported for electric fields, which are not associated with wire codes (Table 7), are not likely to be underestimated.

4.2 Variation in magnetic and electric field exposures

The largest differences in magnetic field exposures were found between provinces, with slight differences between seasons and between days. Our measurement scheme was biased towards summertime measurements in Alberta and Quebec (Figures 3 & 4) but this will only have resulted in a small underestimation of magnetic and small overestimation of electric field levels and does not explain the differences between provinces. To further explore the sources of these differences, statistics on electrical heating and air-conditioning (which together account for the largest portion of residential consumption of electricity) and the percentage of multiple dwelling homes (which are expected to have higher magnetic fields than single-family homes) were obtained for the five provinces (Table 9). (15) When plotted against total 48-h magnetic fields (Figure 7) there is a trend to higher magnetic fields as the proportion of electrically heated, air-conditioned and multiple-dwelling homes increases. Correlations of these three characteristics with total magnetic fields were r=.91, .34 and .64, respectively. From Table 9, the two provinces with the highest percentages of air-conditioned homes (Saskatchewan and Manitoba) were those in which summer magnetic field levels exceeded winter levels.

4.3 Indicators of children's total exposure

For estimating total magnetic fields, sleep exposures were the best surrogates among these control children, but this is not surprising given that the children spent on average 41% of the measurement time sleeping. For electric fields, the best surrogate for total exposure (which excluded sleep) was the at-home exposure. Had the measurement of perturbed electric fields during sleep been possible, it is likely that sleep exposures would have provided a better surrogate of total exposures than the at-home component, given the high proportion of time spent sleeping. Several studies have relied on spot measurements of magnetic fields during the day as an index of total exposure. For example, London et al found correlations of r=.63 and r=.67 between spot measurements in the child's bedroom and 24-h measurements in the same room, under low power and normal power conditions respectively. (3) While we did not explicitly include spot measurements inside homes as part of our protocol, a proxy spot measurement was available from 277 children who had temporarily removed the exposure monitor during measurement, or had not worn it while at home. The median duration of these measurements was 2.3 h, varying between one child who had removed the meter for 6 minutes to another who had not worn it for 34 hours. Locations where the meters were removed had been noted for half of all occurrences. These were: bathroom (32%), child's bedroom (23%), kitchen (14%), family room (12%), parent's bedroom (3%), dining room (2%) and "elsewhere in the house" (13%). Analysis of these proxy spot measurements, identified in Table 6 as "not worn at home," revealed weak correlations with total exposure (r=.31) which improved substantially when logarithms of the measurements were used (r=.72).

How well the total 48-h exposures presented predict long-term mean exposures, assumed to be the exposure metric of greater relevance, depends on exposure variability over the long-term period of interest. Because our two days of measurement were consecutive, the estimated between-day geometric standard deviations we report are likely to be underestimates of their long-term values. (16) Little is currently known about the long-term variability of exposures. Dovan et al (17) in 1990 reported on correlations of spot measurements made five years apart in 81 homes in Denver, Colorado. Correlations ranged from r=.52 for low-power measurements in high-current configuration homes to r=.75 for high power measurements in all homes (Pearson correlations of log-transformed values). In 1993, Bracken and Rankin (18) reported intraclass correlation correlation coefficients for personal exposures measured during repeat visits to homes; these ranged from .44 for very low current configuration homes (VLCC) to .83 for ordinary high current configuration homes (OHCC). Kaune and Zaffanella in 1994 (19) examined correlations between spot measurements and between personal measurements taken eight months apart in spring and in winter. Spot measurements were correlated at .71, similar to the value found by Dovan et al (17), but personal exposures while at home were very weakly correlated (r=.10). When measurements on one visit were used to predict those eight months later, time-weighted average spot magnetic fields, 24-h measurements in the homes and Wertheimer-Leeper wire codes were found to be about equally effective in explaining the between-home variability in personal exposures, with about 30% of the variability explained. Previous personal exposures, however, were found to be ineffective in explaining between-subject variability in personal exposures measured eight months later. (19) However, as the correlations between the personal exposure measurements and residential measurements reported by Kaune and Zafanella were generally lower (r=.28 to .64) than the values found here (r=.74 to .91), the repeatability of personal exposure measurements in our study is expected to be higher.

This report has focussed on the arithmetic mean as the index of children's exposures to ELF fields. Examinations of the relationships of alternative indices of magnetic and electric field exposures among electric utility workers (20)(21)(22) indicate that use of the arithmetic and geometric means at the level of job title generally sacrifices little information on most other indices. For the general population there are to our knowledge no published reports of correlations between various exposure indices. One study of the correlations among indices of occupational and non-occupational exposures of 36 electric utility workers (22) suggests that use of the arithmetic mean might be less effective in the non-occupational setting in identifying the individuals most highly exposed according to other indices. Thus, further investigations of the relationships among alternative indices of exposure in data such as those described would be useful.

5. Conclusion

This study has characterized the distribution and the variability of ELF magnetic and electric field exposures of 365 randomly selected children in five Canadian provinces, using a measurement strategy combining personal exposure monitoring and location diaries. Magnetic field exposures were found to vary substantially between certain provinces, likely due to different housing attributes such as the extent of electrical heating, air conditioning and residence in a multiple dwelling building. The effects of housing attributes on residential magnetic fields are likely to be further modified by exterior temperatures, as indicated by the effect of season on magnetic fields. Overall, magnetic field exposure levels were at their highest while at home during the day and at their lowest during sleep. In contrast to magnetic fields, electric field exposures showed little variation between province, or between activity categories. For prediction of total magnetic field exposures, the best surrogates were measurements of exposures during sleep.

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Table 1 Distribution of control children's time by province

PROVINCE		Home (meter worn)	Home (meter not worn)	School or daycare	Outside home	Bedroom at night	Total
British Columbia	Minutes [a]	685	289	441	350	1251	2440
	n	95	81	56	94	101	102
Alberta	Minutes [a]	671	139	645	327	1250	2586
	n	62	52	37	57	61	62
Saskatchewan	Minutes [a]	606	196	694	206	1202	2535
	n	18	11	16	16	19	19
Manitoba	Minutes [a]	584	264	709	396	1298	2644
	n	23	17	13	21	23	23
Quebec	Minutes [a]	671	272	546	307	1231	2448
	n	150	116	92	139	159	159
All	Minutes [a]	666	248	557	324	1243	2486
	n	348	277	214	327	363	365

[a] Arithmetic mean

Table 2 **Mean 48-h exposure of children to 60-Hz magnetic fields (µT), by province**

		Daytime at home		School		Outside		Sleep		Total
Province	n	AM (95% CI)[§]	n	AM (95% CI)[§]	n	AM (95% CI)[§]	n	AM (95% CI)[§]	n	AM (95% CI)[§]
1. BC	95	.118 (.094, .141)	56	.102 (.077, .134)	94	.123 (.107, .145)	101	.097 (.069, .119)	102	.104 (.085, .122)
2. Alberta	62	.062 (.053, .076)	37	.070 (.049, .089)	57	.073 (.060, .088)	61	.059 (.041, .075)	62	.060 (.050, .070)
3. Saskatchewan	18	.120 (.080, .184)	16	.093 (.059, .188)	16	.087 (.063, .140)	19	.078 (.057, .136)	19	.091 (.072, .131)
4. Manitoba	23	.155 (.125, .205)	13	.156 (.097, .343)	21	.119 (.091, .178)	23	.111 (.085, .161)	23	.133 (.112, .167)
5. Quebec	150	.190 (.163, .225)	92	.141 (.103, .166)	139	.155 (.138, .176)	159	.145 (.122, .188)	159	.155 (.135, .181)
All	348	.141 (.125, .155)	214	.116 (.093, .125)	327	.126 (.116, .138)	363	.112 (.096, .127)	365	.120 (.108, .130)
Sign. of variation between provinces[¥]		<.001		.011		<.001		<.001		<.001

[§] exact 95% confidence limits (22)

[¥] One-way ANOVA on logarithms of 48-h mean values

Table 3 Mean 48-h exposure of children to 60-Hz electric fields (V/m), by province

	Daytime at home		School		Outside		Sleep[¶]		Total["]	
Province	n	AM (95% CI)[¶]	n	AM (95% CI)[¶]	n	AM (95% CI)[¶]	n	AM (95% CI)[¶]	n	AM (95% CI)[¶]
1. BC	95	16.2 (14.4, 18.4)	56	8.8 (7.3, 11.8)	94	17.5 (12.7, 19.8)	101	21.0 (17.8, 27.4)	99	14.9 (13.2, 17.0)
2. Alberta	62	16.9 (14.8, 21.1)	37	7.9 (6.3, 10.7)	57	10.2 (8.9, 12.6)	61	32.5 (22.7, 39.8)	62	12.9 (11.6, 14.6)
3. Saskatchewan	18	15.7 (12.5, 21.0)	16	9.6 (6.0, 24.1)	16	9.9 (7.7, 14.1)	19	17.5 (12.4, 29.2)	19	12.4 (10.1, 16.4)
4. Manitoba	23	18.6 (15.0, 24.3)	13	10.1 (5.9, 22.9)	21	9.8 (7.3, 15.1)	23	13.1 (8.9, 26.5)	23	14.1 (11.1, 18.7)
5. Quebec	150	16.5 (15.1, 18.6)	92	10.1 (8.0, 13.5)	139	15.3 (14.1, 19.7)	159	20.7 (17.5, 26.0)	155	15.0 (13.7, 17.1)
All	348	16.6 (15.7, 17.9)	214	9.3 (8.2, 10.9)	327	14.4 (12.9, 15.9)	363	22.1 (19.6, 25.0)	358	14.43 (13.6, 15.5)
Sign. of variation between provinces[¥]		.82		.99		.11		.005		.88

[§] exact 95% confidence limits (20)

[¥] One-way ANOVA on logarithms of 48-h mean values

[¶] Single axis measurement of unperturbed electric field (meter not worn)

["] Total electric field exposure excludes sleep measurements

Table 4 **24-h bedroom measurements of 60-Hz magnetic fields (µT), by province**

Province	n	AM (95% CI)[§]
1. BC	100	.095 (.069, .116)
2. Alberta	60	.066 (.039, .070)
3. Saskatchewan	18	.069 (.051, .127)
4. Manitoba	23	.112 (.086, .177)
5. Quebec	172	.139 (.127, .180)
All	373	.111 (.097, .128)
Sign. of variation between provinces[¥]	<.001	

[§] exact 95% confidence limits (20)

[¥] One-way ANOVA on logarithms of 48-h mean values

Table 5 Pearson correlations between day 1 and day 2 measurements of 60-Hz magnetic and electric fields

	Magnetic fields AM (lnAM)	Electric fields AM (lnAM)
Worn at home	.605 (.821)	.373 (.561)
Worn at school	.847 (.825)	.466 (.675)
Worn outside home	.376 (.450)	.185 (.441)
Sleep [¥]	.571 (.876)	.413 (.660)
Total exposure	.612 (.789)	.529 (.623)[§]

[¥] meter not worn.

[§] excludes bedroom measurements

values in parentheses are correlations of logarithms

Table 6 **Pearson correlations between activity categories for 48-h measurements of 60-Hz magnetic and electric fields**

	NWH	WH	WSCH	WOUT	SLEEP[□]	TOT[□]	24BR
Not worn at home (NWH)	1	.14 (.38)	.06 (.16)	.02 (.18)	.08 (.32)	.11 (.33)	.05 (.17)
Worn at home (WH)	.41 (.77)	1	.36 (.35)	.17 (.30)	.11 (.29)	.76 (.82)	.05 (.24)
Worn at school (WSCH)	-.004 (.08)	.02 (.16)	1	.12 (.30)	-.02 (.08)	.72 (.67)	-.03 (.08)
Worn outside home (WOUT)	.17 (.54)	.32 (.56)	.26 (.23)	1	-.01 (.06)	.61 (.63)	.09 (.09)
Bedroom at night [¥] (SLEEP)	.25 (.71)	.57 (.74)	.01 (.10)	.34 (.51)	1	.06 (.22)	.80 (.46)
Total exposure (TOT)	.31 (.72)	.74 (.84)	.35 (.46)	.49 (.65)	.91 (.87)	1	.07 (.19)
24 hour bedroom[¶] (24BR)	.67 (.77)	.57 (.78)	.09 (.14)	.33 (.53)	.68 (.88)	.68 (.79)	1

Magnetic field correlations in lower left hand triangle; electric field correlations in upper right handle triangle.

Values in parentheses are correlations of logarithms

[¥] meter not worn.

[§] excludes bedroom measurements

[¶] restricted to 254 homes in which 24-h bedroom measurements were in the same room as the nighttime bedroom measurements

[□] total electric field exposure excludes bedroom at night measurements

Table 7 **60-Hz magnetic and electric field levels associated with Wertheimer-Leeper wire code categories**

Wertheimer-Leeper wiring configuration category [¶]	n	60-Hz magnetic field (μT) AM (95%CI)[§]	n	60-Hz electric field (V/m) AM (95% CI)[§]
UG	66	.093 (.076, .115)	65	12.48 (10.86, 14.34)
VLCC	77	.081 (.068, .098)	77	14.82 (13.10, 16.87)
OLCC	68	.103 (.088, .124)	66	14.99 (13.20, 17.52)
OHCC	88	.169 (.140, .213)	85	16.36 (14.21, 18.64)
VHCC	20	.206 (.158, .299)	20	13.40 (10.27, 24.77)
Total[•]	319		313	

[•] control homes for which wire-codes and total 48-h magnetic fields were available.

[¶] UG: underground; VLCC: very low current configuration; OLCC: ordinary low current configuration; OHCC: ordinary high current configuration; VHCC: very high current configuration

[§] exact 95% confidence limits (20)

Table 8 Distribution of Wertheimer-Leeper wire codes among partipating and non-participating controls

Wertheimer-Leeper wiring configuration category	Participants Frequency	Percent	Non-participants Frequency	Percent
UG	66	19.8	21	23.1
VLCC	81	24.3	14	15.4
OLCC	71	21.3	22	24.2
OHCC	93	27.9	20	22.0
VHCC	22	6.6	14	15.4
Totals	333	100	91	100

Table 9 **Characteristics of homes in five Canadian provinces**

Province	Electricity for space heating (%)[§]	Air conditioners (%)[§]	Multiple dwellings (%)[§]	Total 48-h magnetic field (μT) AM (95% CI)[¶]
British Columbia	27	9	32	.104 (.085, .122)
Alberta	-	8	26	.060 (.050, .070)
Saskatchewan	4	32	19	.091 (.072, .131)
Manitoba	29	48	24	.133 (.112, .167)
Quebec	71	15	47	.155 (.135, .181)

[§] Source: Household Facilities and Equipment, 1994, Statistics Canada, catalogue 64-202

[§] exact 95% confidence limits (20)

Table 10 **Comparison of magnetic field exposures of control or volunteer children across studies**

Geographical area	Season	n	Arithm. Mean	Geometric Mean (of AM)	GSD	Type	Population	Author
United States								
Los Angeles		143	.115	.101		24-h bedroom	Control children, random	London (2)
Washington, DC		29	.131	.099	1.89	24-h personal	Volunteers (< 9y)	Kaune (23)
West Mass., North Cal.	Spr.	30	.112	.084	--	24-h personal	Volunteers (<18y)	Kaune (18)
West Mass., North Cal.	Win.	31	.172	.111	--	24-h personal	Volunteers (<18y)	Kaune (18)
Maryland	Spr.	12	.133	.112	1.81	24-h personal	Volunteers (<11y)	Koontz (24)
Maryland	Win.	11	.194	.145	2.2	24-h personal	Volunteers (<11y)	Koontz (24)
Canada								
British Columbia	Sum.	53	.087	.067	2.15	48-h personal	Random	this paper
British Columbia	Win.	49	.121	.081	2.32	"	"	"
Alberta	Sum.	44	.055	.047	1.70	"	"	"
Alberta	Win.	18	.071	.052	2.23	"	"	"
Saskatchewan	Sum.	8	.096	.085	1.79	"	"	"
Saskatchewan	Win.	11	.088	.077	1.79	"	"	"
Manitoba	Sum.	13	.145	.131	1.65	"	"	"
Manitoba	Win.	10	.117	.111	1.41	"	"	"
Quebec	Sum.	109	.139	.099	2.28	"	"	"
Quebec	Win.	60	.190	.148	2.00	"	"	"
All provinces	Combined	348	.120	.085	2.25	"	"	"

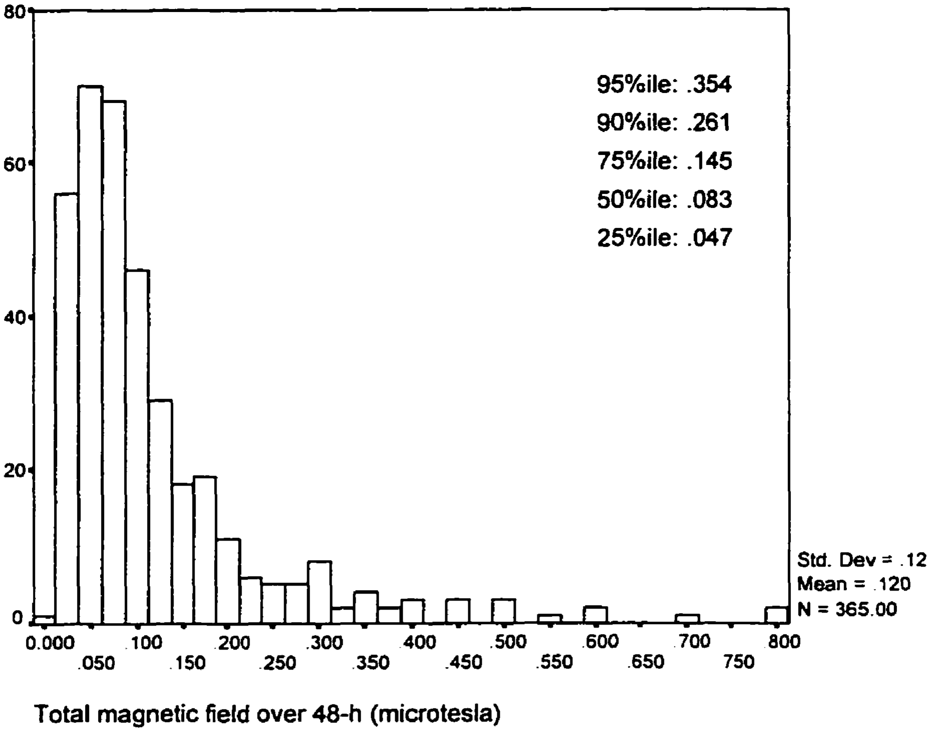

Figure 1
Distribution of control children's exposures to 60-Hz magnetic fields over 48 hours

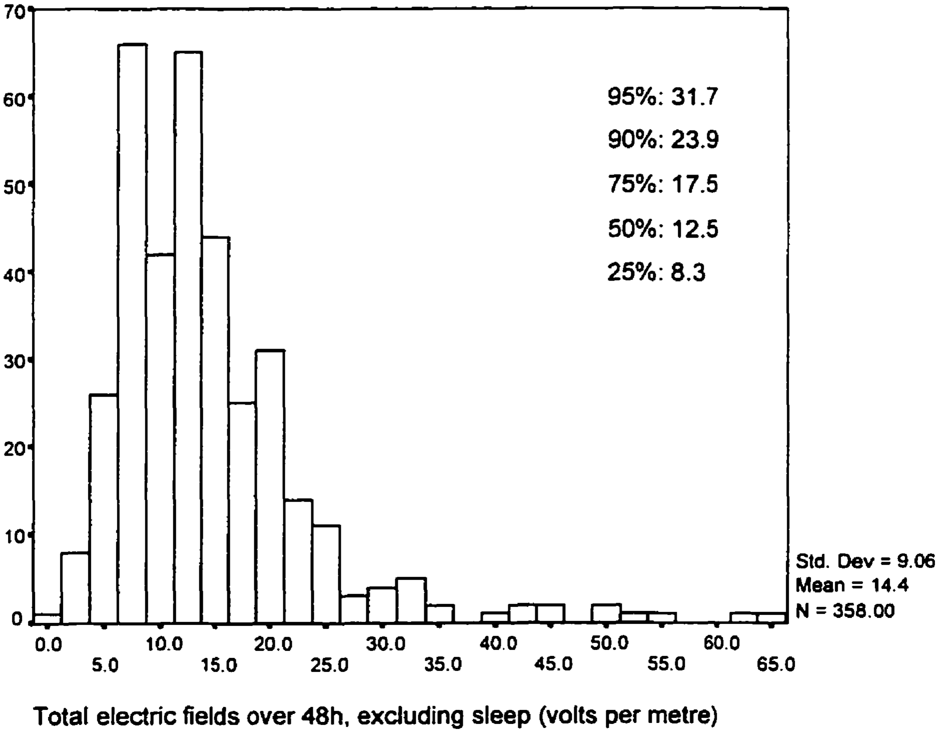

Figure 2
Distribution of control children's exposure to 60-Hz electric fields over 48 hours

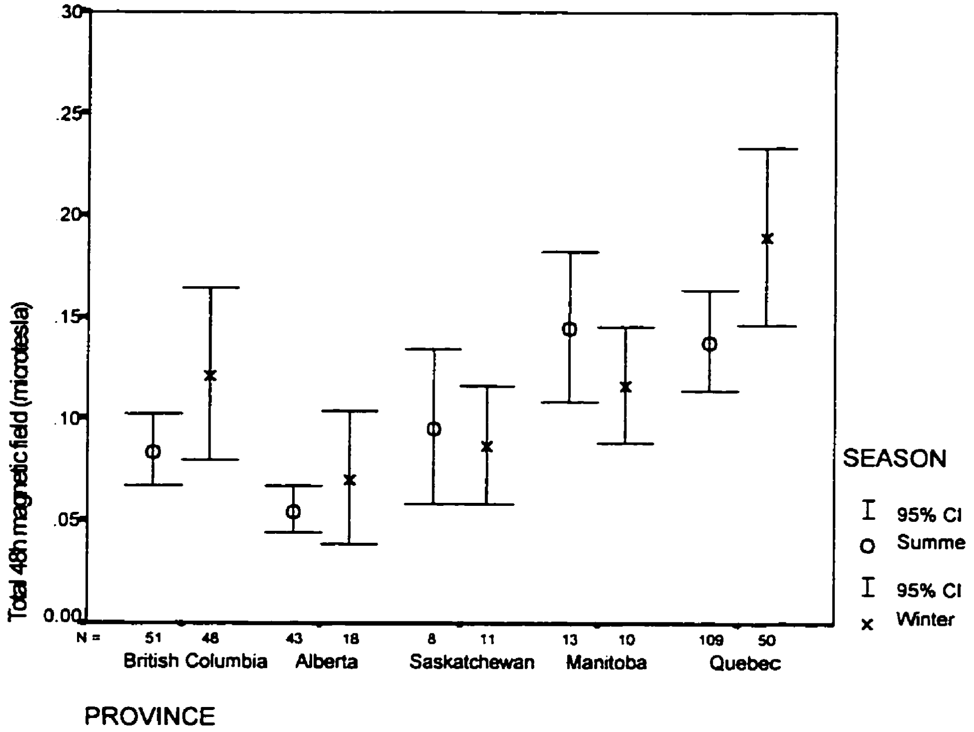

Figure 3
Arithmetic means and 95% CIs of total magnetic fields by province and season

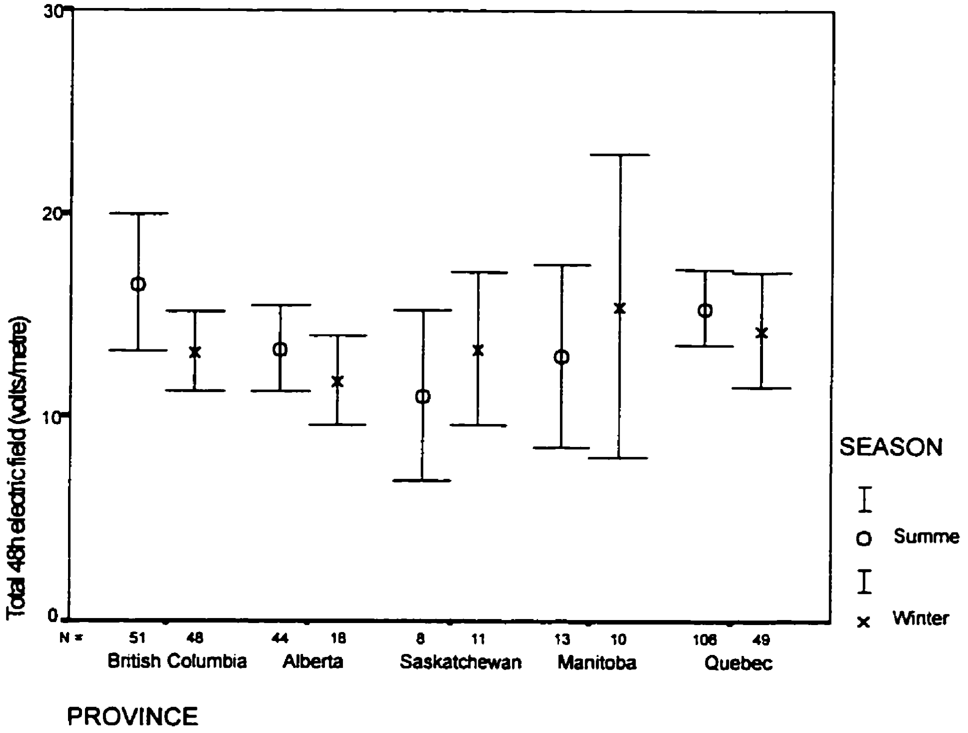

Figure 4
Arithmetic means and 95%CIs of total electric fields by province and season

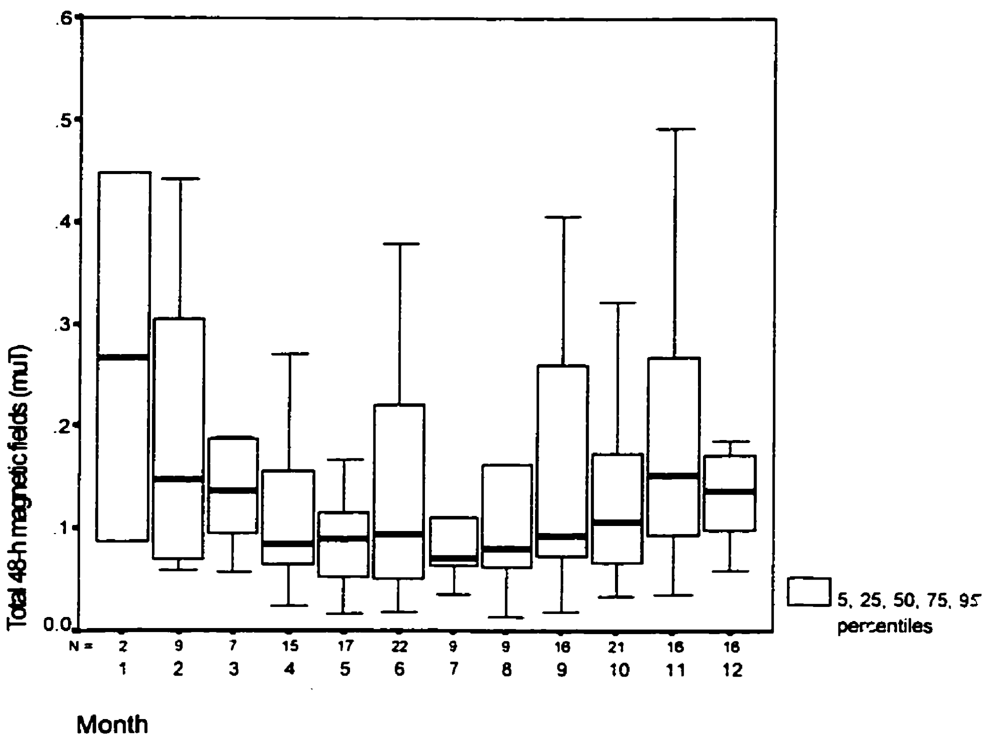

Figure 5
Variation of control children's total 48-h magnetic field exposures by month, Quebec

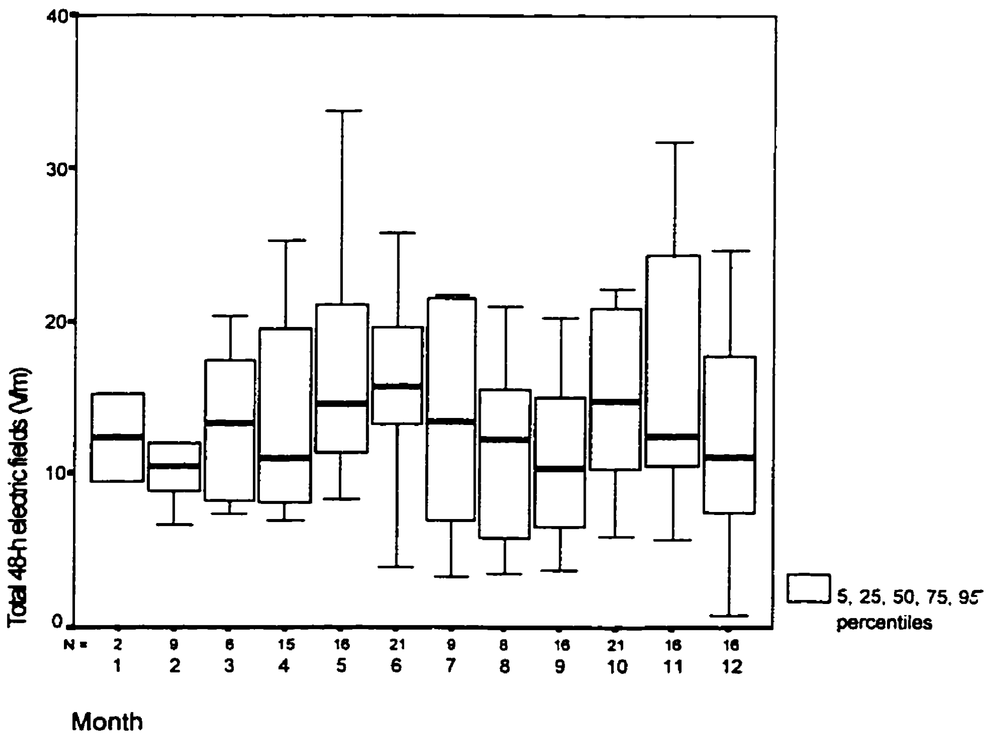

Figure 6
Variation of control children's total 48-h electric field exposures by month, Quebec

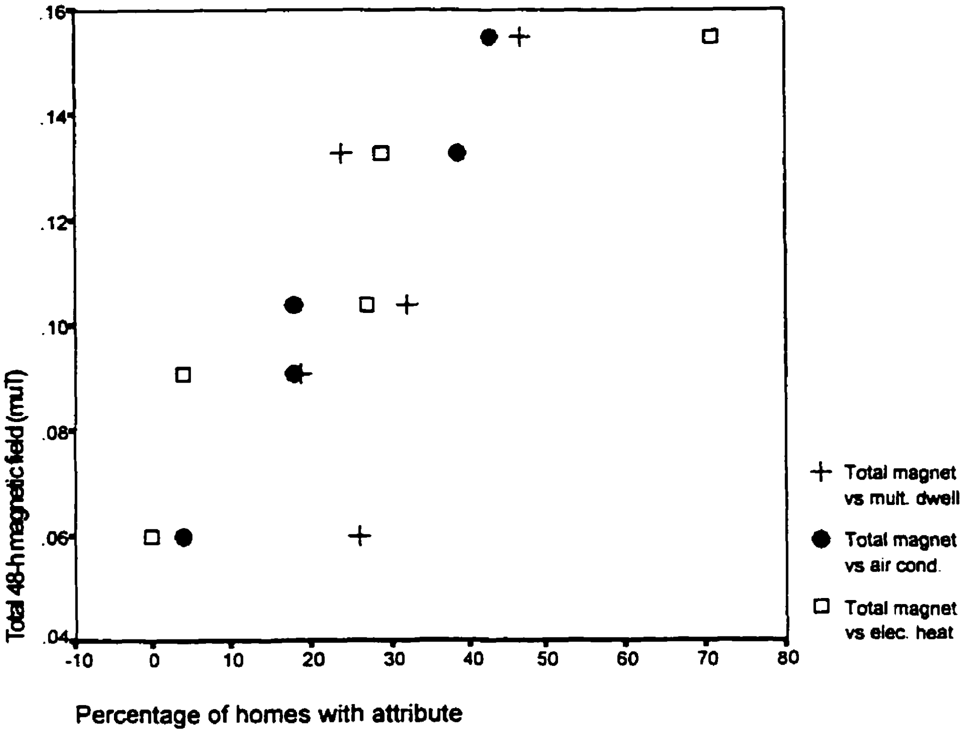

Figure 7
Total magnetic fields as a function of the percentage of homes in each province that were electrically heated, air-conditioned or in multiple dwellings

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6. Conclusion

This thesis has described exposure assessments carried out to characterize the distribution, variability and determinants of exposures to extremely low frequency electric and magnetic fields in occupational and residential settings where no information was previously available. These exposure assessments have improved on previous work by: a/ monitoring personal exposures over extended periods of time; b/ monitoring perturbed electric field exposures; c/ documenting study subjects' activities during monitoring, and for children; d/ monitoring magnetic field exposures during sleep. This thesis has identified important differences in exposures to ELF magnetic and electric fields both among children and among electrical utility workers, and has provided a reference "background" level for these workers.

Indices of exposure

Examination of alternative indices of exposure among electric utility workers has shown that summarizing exposures at the job category level by the arithmetic and geometric means sacrifices little information on other exposure indices, except perhaps the proportion of time spent above certain high and low exposure thresholds. The lack of correlation between magnetic and electric fields in either the occupational or residential settings confirms the need to measure both fields, if exposures to both are of interest, and indicates that exposure reduction strategies will need to address the two fields separately. The alternative exposure indices examined were primarily indicators of the amplitude of the ELF magnetic or electric field. Interest in the possibility that the rate of change of the magnetic field may be more biologically relevant than its amplitude (1)(2) has lead to the proposal of exposure indices that reflect the time-rate of change. (3)(4)

In this thesis, the one index that represented the time rate of change of the magnetic field was highly correlated with the arithmetic and the geometric means of that field, but a variety of other possible rate-of-change indices can be envisaged. It would be useful to understand the patterns of correlations between them.

For residential exposures, there is indication from a previous study that correlations of exposure indices with either the arithmetic or the geometric mean are lower than those found here and in other studies of occupational exposures of electric utility workers. Once the data becomes available in a suitable format, the children's exposure data present an ideal opportunity to examine alternative indices of both the time rate of change and the amplitude of ELF field exposure among children, neither of which have been previously investigated.

Lastly, if one assumes that induced current from both the electric and the magnetic field is the biologically important variable (1) then there is reason to consider an exposure index that combines the effects of both fields. Miller (5) has estimated an equivalence between the two fields from comparison of his measurements of current densities induced by 60-Hz magnetic fields to the measurements by Kaune (6) of current induced by 60-Hz electric fields. Combination of the two fields in this manner can provide a simple exposure metric for studies where exposures to 60-Hz magnetic and electric fields are both of interest.

Task-based exposure estimation

Past exposures were estimated by a novel task-based method that deconstructed total exposures into the *duration* and *intensity* of exposures specific to activities or locations. The method presents several advantages for retrospective or prospective exposure estimation: First, it potentially increases the accuracy of exposure estimation by relying on measured durations of time spent at activities or work locations, and on measured exposure intensities. Further, interviewed subjects are only required to comment on the past durations of their activities; estimates of past intensities can be obtained separately. Second, extrapolating exposures for activities is simpler than for an entire time-weighted average exposure, as the complexity of dealing with activity durations is removed to be dealt with separately. Third, it provides vital information for identifying where and how exposures might be reduced, should that become necessary; activities and sites can be prioritized according to exposure level, and the effects on overall exposure of changes to the duration of an activity or the intensity of exposures during it can be modelled. The method described can apply to contexts other than those described in the thesis, if exposure intensities are measured at the level of activity, and the durations of the activities can be estimated.

Determinants of exposure

The determinants of magnetic field exposure investigated in this thesis explained about half of the variability of occupational exposures but only about one-fifth of the residential exposure variability. From the data available, four factors were identified as potentially important determinants of residential exposure to magnetic fields, and warrant more detailed investigation: the extent of electrical heating, air conditioning, residence in a multiple dwelling, and exterior temperature. A combined function of these factors might provide more accurate prediction of residential magnetic fields. The effect of temperature should also be considered during estimation of exposures for occupations involving work close to power distribution or power transmission lines: as indoor temperature departs from comfort levels, the increased electrical heating or cooling load carried by these lines will result in higher magnetic field levels near them. Future studies of these occupations should also include careful documentation of the current loads on equipment and power lines in the workers' vicinities. Examination of the relationships between conditions at the time of measurement and ELF field levels will allow greater confidence when present exposure estimates are extrapolated to the past, or to the future should the control of exposures become necessary. Further improvements to the retrospective estimation of ELF field exposures could be achieved by identifying the specific sites where study subjects had worked in the past and by obtaining records of past conditions on lines and other electric utility equipment applicable to these sites.

Long-term exposure estimation

When viewed from a longer time perspective, the exposures reported here for the electrical utility workers and for the control children represent but a single measurement episode. Their usefulness in predicting long-term exposures, for example over a year, will depend on the day-to-day variability over the year. Repeat measurements of exposures combined with observations of conditions at the time of measurement will help in understanding how exposures vary over time, thus improving the accuracy of long-term exposure estimation. In cases where random repeat measurements impose overwhelming logistical difficulties, a natural extension of the task-based estimation method could provide a simpler alternative: Olsen has described an exposure estimation method (7) in which subjects keep logs of the durations of their tasks or activities over several weeks, to improve the accuracy of the estimates of exposure duration. This information is then combined with measurements of the intensity of exposure during several instances of the task or activity, thus improving the accuracy of the estimates of long-term exposure.

The potential health effects of exposures to extremely low frequency electric and magnetic fields continue to be of appreciable scientific and public concern. Improvement of the validity of exposure assessments to these fields, through the directions suggested here and through other methods, is vital not only to studies examining the effects of their exposures but also to programmes that seek to monitor or reduce the exposures.

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IMAGE EVALUATION
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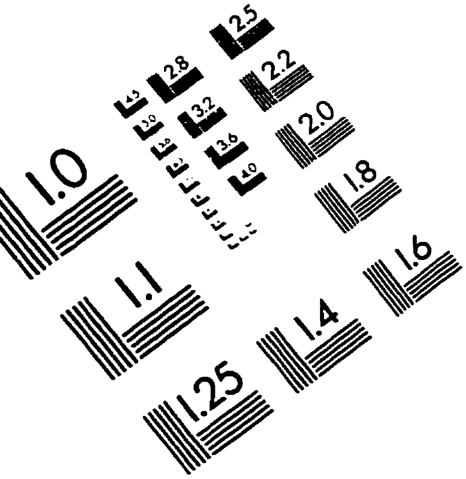
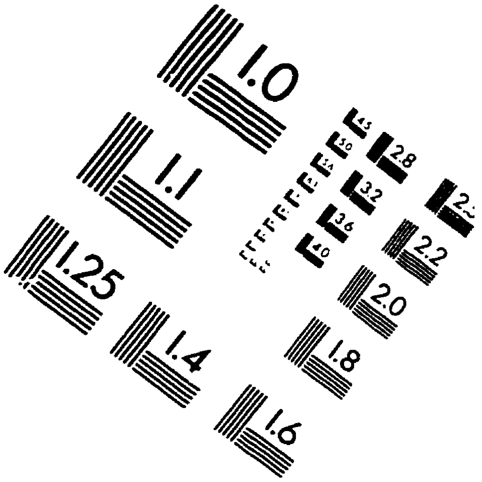
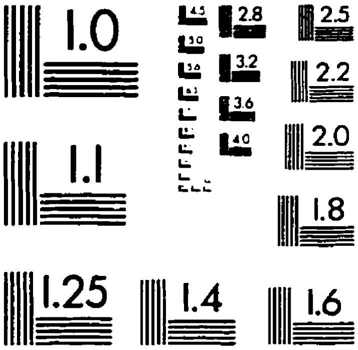

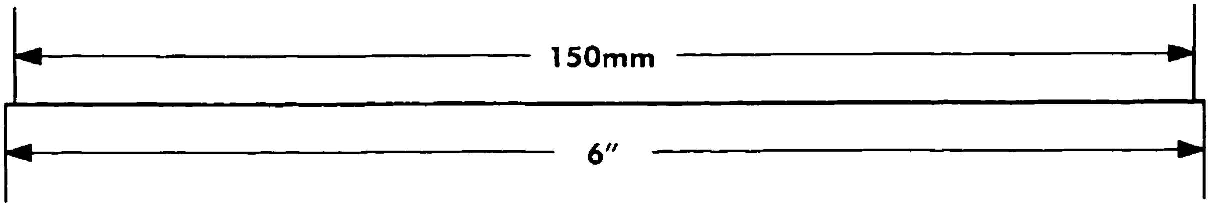

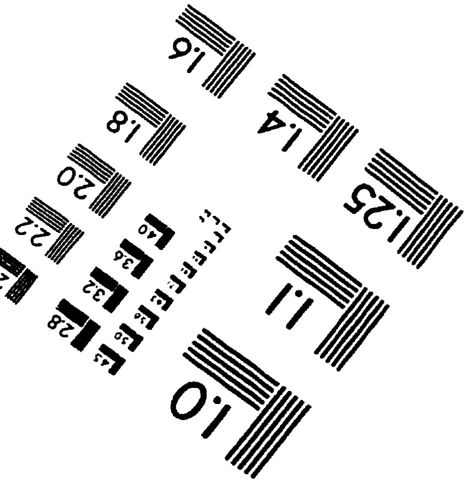
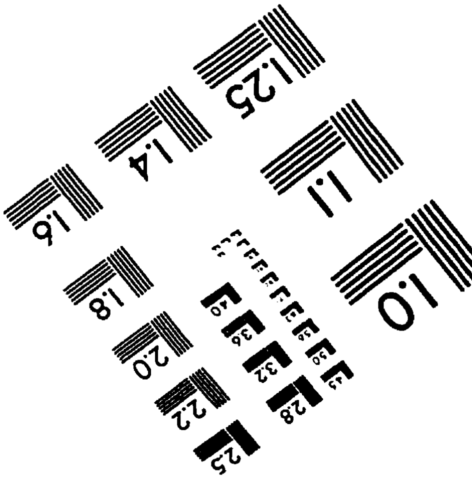

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