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Alternate Indices of Electric and Magnetic Field Exposures Among Ontario Electrical Utility Workers

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Epidemiologic studies examining the risk of cancer among occupational groups exposed to electric fields (EF) and or magnetic fields (MF) have relied on traditional summaries of exposure such as the time weighted arithmetic or geometric mean exposure. Findings from animal and cellular studies support the consideration of alternative measures of exposure capable of capturing threshold and intermittent measures of field strength. The main objective of this study was to identify a series of suitable exposure metrics for an ongoing cancer incidence study in a cohort of Ontario electric utility workers. Principal components analysis (PCA) and correlational analysis were used to explore the relationships within and between series of EF and MF exposure indices. Exposure data were collected using personal monitors worn by a sample of 820 workers which yielded 4247 worker days of measurement data. For both EF and MF, the first axis of the PCA identified a series of intercorrelated indices that included the geometric mean, median and arithmetic mean. A considerable portion of the variability in EF and MF exposures were accounted for by two other principal component axes. The second axes for EF and MF exposures were representative of the standard deviation (standard deviation) and thresholds of field measures. To a lesser extent, the variability in the exposure variable was explained by time dependent indices which consisted of autocorrelations at 5 min lags and average transitions in field strength. Our results suggest that the variability in exposure data can only be accounted for by using several exposure indices, and consequently, a series of metrics should be used when exploring the risk of cancer owing to MF and EF exposure in this cohort. Furthermore, the poor correlations observed between indices of MF and EF reinforce the need to be take both fields into account when assessing the risk of cancer in this occupational group. *Bioelectromagnetics 19:140–151, 1998.* © 1998 Wiley-Liss, Inc.

Key words: PCA; principal component analysis; effects function; exposure metrics; exposure indices

INTRODUCTION

Epidemiological studies of workers with high exposure to magnetic fields have inconsistently demonstrated an increased risk of brain cancer and leukemia [Sahl et al., 1993; Coleman and Beral, 1988; Savitz et al., 1995; Floderus et al., 1993; Thériault et al., 1994; Harrington et al., 1997]. Equivocal results have also been obtained from a limited number of studies of electric utility workers that investigated the relationship between electric fields and cancer [Guénel et al., 1996; Miller et al., 1996].

At this time, no clear health or biologic effects resulting from exposure to electric and magnetic fields have been established. In addition, there is no widely accepted biophysical model to predict relevant exposure. For these reasons, there is uncertainty with regards to the exposure metric, or dose, used to evaluate biological effects in epidemiologic studies. In studies of electric utility workers, the association between EMF and cancer has typically been evaluated with a time-weighted average (TWA) measure of exposure. Several experimental studies suggest that other aspects of field exposure are relevant to the study of cancer. Intermittent exposures of EMF have been shown to promote tumours in rodents while no such increase

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in tumour risk was observed with constant exposures [Beniashvili et al., 1991; Rannug et al., 1994]. Tumor promoting agents are capable of converting a cancer-initiated cell to a potentially malignant cell and are characterised by the reversibility of their effects and the existence of a threshold [Pitot and Dragan 1991]. Some other experimental studies support the theory that EMF serves as a tumor promoter [Mevissen et al., 1993, 1996; Baum et al., 1995; Liburdy et al., 1993; Byus et al., 1987] whereas others have not [Dees et al., 1996; McLean et al., 1997; Loscher et al., 1994; Lacy–Hubert et al., 1995]. A linear relationship between magnetic field flux density and mammary tumours has been noted [Loscher and Mevissen, 1995]. It has also been suggested that for a given field strength, short duration exposures may cause significantly larger bioeffects than exposure for much longer or much shorter times [Litovitz, 1992]. The findings of the studies listed above underscore the need to further examine the relationship between various measures of exposures. A comprehensive review of cellular and biological studies is contained in recently published work [Holmberg, 1995; National Research Council, 1997].

The goal of this study was to examine the correlations within and between a series of electric and magnetic field exposure summaries using Principal Components Analysis (PCA). Identifying metrics that are highly correlated enables redundant metrics to be eliminated. Conversely, poorly correlated metrics can be useful in identifying independent aspects of exposure. PCA represents a suitable and objective means to reduce a large number of exposure indices to a smaller, more manageable subset that best captures the variability in exposure data.

Similar methodology has previously been employed to examine summary measures of magnetic fields [Sahl et al., 1994; Zhang et al., 1997]. Our study builds upon this analysis by examining EF in addition to MF exposures as well as by considering a greater variety of exposure metrics. Correlational analyses have also been used to evaluate different possible metrics [Armstrong et al., 1990; Breysse et al., 1990; Savitz et al., 1994; Wenzl et al., 1995; Zhang et al., 1997]. However these studies were limited by small sample size [Armstrong et al., 1990], incomplete ascertainment of electric field metrics [Breysse et al., 1994; Savitz et al., 1994; Wenzl et al., 1995; Zhang et al., 1997] and exposure assessment in non electric utility workers [Breysse et al., 1990; Wenzl et al., 1995].

This study uses electric and magnetic field measures that were collected in a sample of 820 Ontario electric utility workers using the POSITRON monitor. This monitor records field measures according to a series of 16 bins, every minute, over the course of a work-day, and therefore, a large number of exposure metrics could conceivably be created. The development of new metrics was done after a review of the biological and epidemiological literature. We defined metrics that were based on the results of animal and cellular studies, and also looked at defining other metrics for which there was no research information. The biological database relevant to 'other metrics' is limited. Most studies have used continuous exposure at one or more field intensities, and most have used magnetic field exposure systems only. For those cases where effects have been reported, there has generally been little success in replicating them in other independent laboratories. To our knowledge, no biological study has reported a significant positive finding and then proceeded to investigate different categories of exposure metrics, nor do we know of any research that eliminates specific metric categories from contention. We felt the need to fully explore our study which reported a positive finding [Miller et al., 1996] and employed a monitor that recorded electric and magnetic fields each minute during the workday.

We refer to metrics that have commonly been used in epidemiological studies as traditional exposure indices and, of these, our analyses included the geometric mean, arithmetic mean, standard deviation, ninety-fifth percentile and median. Alternate measures of exposure were constructed from the recorded monitor readings and are referred to as '*non-traditional*' indices. The indices included percentage of time spent above a threshold, average transistion in field strength, arithmetic geometric average at or above a threshold, time spent above a threshold for a minimum duration, and autocorrelations at various lags.

MATERIALS AND METHODS

Electric and Magnetic Field Exposure Assessment

Direct measurements of worker exposure under usual working conditions were obtained using the Positron model 378108 personal exposure monitor (Positron Industries, Montreal, Quebec, Canada). The Positron is a portable pocket sized, battery operated electronic instrument designed to monitor immediate personal environmental exposure to 50/60 Hz magnetic and electric fields. The Positron monitor filters the electric and magnetic field signal to limit the measurement to 60 Hz fields. The devices were used to record EF and MF in the environment each minute. Each reading was assigned according to 16 predefined exposure intervals or bins. The exposure intervals were 0–0.61, 0.61–1.22, 1.22–2.44 · · · 5,000–10,000, >10,000 V/m

TABLE 1. List of Electric Field Exposure Indices (n = 38)

Group variable name	Number of metrics	Description
1. ET_TH{x}	4	Percentage of time the EF is at or above x = {40, 156, 625, or 2500 V/m}
2. EAV_TH{x}	8	Arithmetic mean* of EF at or above x = {40, 156, 625, or 2500 V/m}
3. EGAV_TH{x}	8	Geometric mean* of EF at or above x = {40, 156, 625 or 2500 V/m}
4. EJAG	1	Percentage of EF samples that differ by at least 2 bins
5. E_AVTRAN	2	Average* EF transition in number of bins for adjacent samples taken 1 min apart
6. ETD{x}_{y}	3	Percentage of time at or above x = 40 for at least y = {5, 15 minutes} and x = 156 for at least y = {5 min}
7. LAG_E_{x}	4	Autocorrelations of x = {1, 5, 15 or 30 min lags}
8. ITD{x}_{y}	3	Average of values at or above x = 40 V/m for at least y = {5, 15 min} and x = 156 V/m for at least y = {5 min}
9. EAV_TH11	1	Arithmetic mean
10. EGAV_TH1	1	Geometric mean
11. E_MEDIAN	1	Median
12. E_STD	1	Standard deviation of electric field measure (in V/m)
13. E_95	1	95th percentile

*The average was calculated using (i) total time above the threshold and (ii) the total time for the period.

for electric fields and 0–0.12, 0.12–0.24, 0.24–0.48, . . . , 100–200, >200 μT for magnetic fields. Each measure was assigned the value of the midpoint of the interval. The monitors were tested and calibrated before use and at regular intervals during the study. A more detailed description of this monitor as well as its ability to differentiate exposures by occupational group and to obtain high compliance in workers has previously been published [Héroux, 1991; Deadman et al., 1988].

Measurements were originally performed on 895 workers, sampled by job title and work location. These measures were taken over the course of a five day work week and were defined by person, occupational group, work site and day. Our analyses are based on the measures of electric and magnetic fields of 820 workers from 17 occupational groups. Those with only electric or magnetic field exposure were not included, and this accounts for most of the 75 workers removed from the 895 used in the Tri-Utility Study [Thériault et al., 1994]. The missing data from these 75 was due to instrument failure, or strong evidence that the monitor was kept close by (and so suitable for magnetic field exposure estimates) but not worn (and therefore not valid electric field data). There were 2 worker records that could not be retrieved due to defects that appeared in the discs containing the raw data required to calculate the new metrics.

Although estimates of home exposures were made for a sample of workers, these estimates were not included in these analyses as the primary objective was to evaluate occupational exposures.

Exposure Metrics

Only those thresholds above the mean exposure level of all workers were considered in our analyses. It was also decided to exclude those metrics where positive exposures occurred in less than five percent of the worker days. For example, on only 16 of 4247 worker days (0.4%) was a worker exposed to a threshold of 200 μT for a continuous interval of 15 min. Therefore this metric was dropped. We felt that these metrics, which were typically high threshold exposures for a minimum period of time, would have little power to discriminate disease status in subsequent case-control analyses. In total, 33 and 34 ‘non-traditional’ metrics of electric and magnetic, respectively, were included in our analysis (Tables 1, 2).

Statistical Analyses

Principal components analysis (PCA) may be used to analyse a set of interrelated variables. The original variables are transformed into a smaller set of uncorrelated variables that are referred to as principal component axes. An axis is a linear combination of a subset of variables with which it has high correlation.

TABLE 2. List of Magnetic Field Exposure Indices (n = 39)

Group variable name	Number of metrics	Description
1. MT_TH{x}	3	Percentage of time the MF is at or above x = {3, 12.5, or 50 μT}
2. MAV_TH{x}	6	Arithmetic mean* of MF at or above x = {3, 12.5, or 50 μT}
3. MGAV_TH{x}	6	Geometric mean* of MF at or above x = {3, 12.5, or 50 μT}
4. MJAG	1	Percentage of MF samples that differ by at least 2 bins
5. M_AVTRAN	2	Average* MF transition in number of bins for adjacent samples taken 1 min apart
6. MTD{x}_{y}	6	Percentage of time at or above x = 3 μT for at least y = {5, 15, 30 or 60 min} and x = 12.5 μT for at least y = {5, 15} min
7. LAG_M_{x}	4	Autocorrelations of x = {1, 5, 15 or 30 min lags}
8. NTD{x}_{y}	6	Average of values at or above x = 3 μT for at least y = {5, 15, 30 or 60 min}, and x = 12.5 μT for y = {5, 15 min}
9. MAV_TH1	1	Arithmetic mean
10. MGAV_TH1	1	Geometric mean
11. M_MEDIAN	1	Median
12. M_STD	1	Standard deviation of magnetic field (in μT).
13. M_95	1	95th percentile

*The average was calculated using (i) total time above the threshold and (ii) the total time for the period.

One purpose of PCA is data reduction achieved by explaining as much of the total variation in the complete set of variables with as few factors (principal components) as possible. The principal component axes are uncorrelated, thus identifying independent sources of variability. PCA is a frequently used tool in questionnaire design and validation and is described in many biostatistical texts [Reyment and Jöreskog, 1993; Kleinbaum et al., 1988; Rawlings et al., 1988].

When PCA is applied to exposures of EF and MF, the axes are summary measures which are representative of those exposure metrics that are most highly correlated with them. These axes are ordered by the amount of variability they explain, that is by their variance. The number of factor axes are determined based on the variances obtained from the correlation matrix of the PCA. In all our analyses, factor axes with variance greater than one were retained. PCA represents an objective means of data reduction and identification of independent aspects of exposure.

PCA was performed on electric and magnetic fields separately. The principal component axes were rotated so as to maximize correlations of a smaller number of metrics with each axis. The Varimax rotation method was used which maintained the orthogonality of the axes derived from the PCA [Reyment and Jöreskog, 1993]. However, because the rotated axes correlate with fewer metrics, the ability to identify important metrics was improved.

PCA was performed in three stages. First, PCA was performed only on the '*non-traditional*' exposure summaries as a means of data reduction. Traditional measures were not included in these analyses because their exposure patterns would be overwhelmed by the large number of '*non-traditional*' exposures. Indeed, preliminary analysis of our data demonstrated that this was the case. The first stage of PCA yielded a series of factor axes. From these, the metric that was most highly correlated with each axis was selected and retained for further analyses. Selecting metrics in such a manner removed those metrics that were redundant.

In the second stage of analyses, PCA was performed on those metrics selected in the first stage in conjunction with the *'traditional'* metrics of exposure. This allowed us to examine the relationships between the selected signals and the traditional measures of exposure. Correlation matrices of the exposure indices that were highly correlated with the factor axes derived in the second stage PCA were constructed. This enabled us to further evaluate the relationships between our selected metrics as well as to make comparisons to previous studies that have used this technique [Armstrong et al., 1990; Savitz et al., 1994].

Finally, PCA of the selected metrics and traditional exposure summaries was done within occupational groupings. Analysis was done individually for each of the 17 occupational groups. In addition, separate analyses were conducted in subsets of workers

TABLE 3. Indices of Exposure Selected to Represent each Principal Component Factor Axis for 'Non-Traditional' Electric Field Exposures Among a Sample of Ontario Electric Utility Workers

Axis	Metric	Description	Axis variance	Correlation with axis
1.	ET_TH14	Percentage of time at or above 2500 V/m	12.3	0.95
2.	EAV_TH10	Arithmetic mean of field at or above 625 V/m	6.2	0.94
3.	ETD8_5	Percentage of time at or above 40 V/m for at least 5 min	3.7	0.94
4.	LAG_E_5	Autocorrelation at a lag of 5 min	3.3	0.92
5.	E_AVTRAN	Average EF transition in number of bins for adjacent readings	2.0	0.95
6.	EAV_TH14	Arithmetic mean of electric field at or above 2500 V/m	1.6	0.62

with high exposures to magnetic fields. These analyses allowed us to determine which metrics best accounted for the variability of exposure by occupational group and permitted comparisons to results derived using all workers.

RESULTS

Electric Fields

PCA on the 33 '*non-traditional*' electric field metrics yielded six factor axes. The electric field metrics that were selected to represent each of these axes are displayed in Table 3. The first axis accounted for 42% of the overall variance among electric field exposures. This axis appeared to be representative of percentage of time spent above a threshold. The metric that was most highly correlated with this axis was the percentage of time at or above 2500 V/m ($r = 0.95$). Similarly, the second axis was representative of the arithmetic mean of signals at or above 625 V/m ($r = 0.94$).

PCA on the selected six metrics and traditional measures yielded three factor axes. The geometric mean, arithmetic mean, median and the percentage of time at or above 2500 V/m were highly correlated with the first factor axis (Table 4). The arithmetic mean at or above 625 V/m ($r = 0.81$) the arithmetic mean of EF at or above 2500 V/m ($r = 0.86$) and the standard deviation ($r = 0.77$) were most highly correlated with the second factor axis. The average EF transition and autocorrelation at a 5 min lag were highly correlated with the third factor axis. However, the overall proportion of variability explained by this axis was only 16%.

Correlations between the metrics that were highly correlated with the factor axes from the second stage PCA are presented in Table 5. The median and geometric mean were highly correlated with each other ($r = 0.92$) but less tightly with the arithmetic mean ($r < 0.80$). Similarly, the percentage of time at or above 2500 V/m was highly correlated with the geometric mean and the median. The arithmetic mean was correlated with the standard deviation ($r = 0.81$). The standard deviation and the arithmetic mean of the EF at or above 2500 V/m, which were both correlated with the second factor axis, were modestly correlated with each other ($r = 0.71$). Finally, the metrics that were most highly correlated with the third factor axis were uncorrelated with each other. These metrics consisted of the average transition in the EF and autocorrelation at a lag of 5 min ($r = -0.29$). Moreover, these metrics were uncorrelated with all of the other exposure metrics included in the PCA ($r < 0.30$).

The mean daily EF exposures for each of the traditional electric field metrics, by occupational group are presented in Table 6. PCA performed separately for each of the occupational groups yielded between two and four factor axes [results not shown]. The median and geometric mean were both highly correlated with either the first or second factor axis in 16 of 17 of the occupational groups ($r > 0.8$). The standard deviation was typically highly correlated with a factor axis that was not representative of the geometric mean\median.

Magnetic Fields

PCA of the 34 non-traditional measures of magnetic fields resulted in six factor axes (Table 7). The first axis accounted for approximately 42% of the variance of the exposure indices. The MF average at or above 3 μT for at least 5 min was most highly correlated with the first axis ($r = 0.97$) and was retained for further analyses. Similarly, the percentage of time spent above 0.8 μT for at least 5 min was most correlated with the second factor axis ($r = 0.95$). As with electric fields, the 6 metrics that were most correlated with each of the factor axes were retained for further analysis.

PCA of the selected non-traditional metrics and traditional summaries yielded three factor axes (Table 8). High correlations with the first axis were observed for the geometric mean, the median and the geometric mean of MF exposures at or above 0.8 μT for at least

TABLE 4. Principal Component Analyses* of Selected Electric Field Metrics and Traditional Measures of Exposure Among Ontario Electric Utility Workers

		Axis #1	Axis #2	Axis #3
Non-traditional exposure summaries				
Metric	*Description*			
ETD8_5	Percentage of time at or above 40 V/m for at least 5 min	0.54	0.16	0.34
LAG_E_5	Autocorrelation at a 5 min lag	0.09	0.08	**0.83**
ET_TH14	Percentage of time at or above 2500 V/m	**0.88**	0.31	−0.04
EAV_TH14	Arithmetic mean of electric field at or above 2500 V/m	0.12	**0.86**	−0.01
EAV_TH10	Arithmetic mean of electric field at or above 625 V/m	0.13	**0.81**	−0.08
E_AVTRAN	Average EF transition in number of bins for adjacent readings	0.00	0.17	**−0.73**
Traditional exposure summaries				
Metric	*Description*			
EAV_TH1	Arithmetic mean	**0.88**	0.41	0.00
EGAV_TH1	Geometric mean	**0.93**	0.01	0.09
E_MEDIAN	Median	**0.93**	−0.01	0.03
E_95	95 percentile	0.73	0.45	0.03
E_STD	Standard deviation	0.57	**0.77**	0.00
Variance explained by each factor axis		4.47	2.67	1.35

*The principal component axes were rotated using the Varimax method; traditional and non-traditional measures of exposure were analyzed simultaneously.

TABLE 5. Correlation Matrix of Selected Electric Field Metrics* and Traditional Measures of Electric Field Exposure among Ontario Electric Utility Workers

	LAG_E_5	ET_TH14	EAV_TH1	EAV_TH14	EGAV_TH1	EAV_TH10	E_AVTRAN	E_MEDIAN	E_STD
LAG_E_5	1.00								
ET_TH14	0.10	1.00							
EAV_TH1	0.14	0.96	1.00						
EAV_TH14	0.01	0.39	0.45	1.00					
EGAV_TH1	0.12	0.76	0.77	0.19	1.00				
EAV_TH10	−0.04	0.38	0.43	0.72	0.77	1.00			
E_AVTRAN	−0.29	0.03	0.06	0.13	−0.08	0.10	1.00		
E_MEDIAN	0.10	0.80	0.78	0.17	0.92	0.13	−0.06	1.00	
E_STD	0.10	0.74	0.81	0.71	0.49	0.54	0.13	0.46	1.00

*A description of the variable names used to represent the metrics can be found in Table 1.

5 min ($r > 0.90$). The standard deviation ($r = 0.93$) and the ninety-fifth percentile ($r = 0.78$) were highly correlated with the second factor axis. The arithmetic mean of the magnetic field at or above 3 μT was moderately correlated with the second factor axis ($r = 0.67$). Autocorrelations at a lag of 5 min ($r = 0.83$) and the average magnetic field transition in number of bins ($r = -0.71$) were most highly correlated with the third factor axis.

The correlations between those indices that were highly correlated with the factor axes in the second stage of PCA are presented Table 9. The geometric mean and median are tightly correlated with each other ($r = 0.92$), but less so with the arithmetic mean ($r = 0.81$, $r = 0.78$). The geometric mean of MF at or above 0.8 μT was highly correlated with the geometric mean and the median ($r > 0.85$). As had been found for electric fields, the metrics correlated with the third factor axis were uncorrelated to each other and to the other metrics ($r < 0.30$). These metrics consisted of autocorrelation at a 5 min lag and the average transition of MF in number of bins.

The mean values of traditional exposure indices of MF, by occupational group, are presented in Table 10. When PCA was performed separately by occupational group, the number of factor axes that resulted ranged from 2 to 4 [results not shown]. The geometric mean and median were both highly correlated ($r > 0.85$) with the first or second factor axis in all 17 occupational groups. In 15 of 17 groups, the standard deviation was most highly correlated with a factor axis that was not representative of the geometric

TABLE 6. Mean Daily Exposure (in V/m) for Traditional Measures of Electric Fields, by Occupational Group, Ontario Electric Utility Workers

Occupational group	Arithmetic mean	Geometric mean	Median	Standard deviation	95th Percentile
Clerk	11.00	5.11	5.79	23.30	33.08
Control maintainer	7.57	2.42	2.58	37.98	17.71
Customer service rep	11.14	5.77	6.78	21.65	29.92
Foresters	28.14	3.84	3.96	90.34	129.08
Inspector	5.46	1.74	1.71	14.44	23.09
Meter reader	7.61	3.08	3.16	18.19	26.60
Operators	12.79	2.99	3.56	62.45	34.57
Powerline maintainer	75.99	11.56	14.52	196.20	368.34
Professional and manager	6.90	2.28	2.43	29.89	21.05
Power maintenance elect	60.79	6.49	9.16	188.20	271.16
Stockkeeper	9.62	2.24	2.49	37.93	37.84
Supervisor–tech & trade	14.31	4.86	5.06	46.71	43.93
Truck driver	18.09	3.36	2.97	44.06	74.15
Maintenance and security	22.41	4.77	6.00	67.04	92.96
Technical-other	9.85	3.07	3.43	30.81	34.76
P&C Tech	13.71	2.32	2.26	67.72	35.20
Trade–general	8.54	2.91	3.87	30.05	24.44
All groups	22.12	4.51	5.38	67.98	91.40

TABLE 7. Indices of Exposure Selected to Represent each Principal Component Factor Axis for 'Non-Traditional' Magnetic Field Exposures Among a Sample of Ontario Electric Utility Workers

Axes	Metric	Description	Axis variance	Correlation with axis
1.	NTD10_5[a]	Average of values at or above 3 μT for at least 5 min	12.2	0.97
2.	MTD8_5	Percentage of time at or above 0.8 μT for at least 5 min	5.7	0.95
3.	MAV_TH10	Arithmetic mean of magnetic field at or above 3 μT	5.0	0.96
4.	LAG_M_5	Autocorrelation at a 5 min lag	3.1	0.91
5.	M_AVTRAN	Average MF transition in number of bins for adjacent readings	2.0	0.96
6.	NGAV_TH8[a]	Geometric mean of magnetic field at or above 0.8 μT	1.3	0.59

[a]Average calculated with the denominator being the total time period not total time above a threshold.

mean\median. When analysis was limited to workers with high exposures to magnetic field (i.e. operators, power maintenance electricians and P&C Technicians) three factor axes emerged (Table 11). The geometric mean ($r = 0.96$), standard deviation ($r = 0.86$) and autocorrelation at a 5 min lag ($r = 0.85$) were correlated with the first through third axes respectively.

EF and MF fields are weakly correlated with each other (Table 12). The maximum correlation observed between the five traditional measures of EF and those of MF was $r = 0.42$. The correlation between traditional indices of EF and MF was even weaker ($r < 0.10$) when only workers with high exposures to MF were considered [results not shown].

DISCUSSION

Our PCA suggests that the variability in EF and MF signals can be represented by three independent aspects of exposure. The majority of the variability of EF and MF exposures is accounted for by measures of central tendency, the standard deviation and indices representative of thresholds. To a lesser extent, variability of EF and MF exposures is explained by temporal metrics. These include autocorrelation at a 5 min lag and the average transition in field strength. Moreover, the indices of EF and MF are uncorrelated implying that both field exposures should be used when evaluating the risk of cancer.

In the identification of a set of EF and MF exposure variables that predict the probability of cancer in a multivariate model, an exposure variable is more likely to be selected as an important contributor if it fulfills three conditions. These conditions are that it be highly variable, be poorly correlated with the other variables in the model and along with these other variables be highly correlated to the probability of disease. Our analyses using PCA and correlation analyses iden-

TABLE 8. Principal Component Analyses* of Selected Magnetic Field Metrics and Traditional Measures of Exposure among Ontario Electric Utility Workers

		Axis #1	Axis #2	Axis #3
Non-traditional exposure summaries				
Metric	*Description*			
MTD8_5	Percentage of time at or above 0.8 μT	0.54	0.20	0.38
LAG_M_5[a]	Autocorrelation at a 5 min lag	0.03	0.10	**0.83**
NGAV_TH8	Geometric mean of magnetic field at or above 0.8 μT	**0.91**	0.21	−0.08
NTD10_5[a]	Average of values at or above 3 μT for at least 5 min	0.66	0.61	0.09
MAV_TH10	Arithmetic mean of magnetic field at or above 3 μT	−0.03	0.67	−0.19
M_AVTRAN	Average magnetic field transition in number of bins for adjacent samples	−0.05	0.21	**−0.71**
Traditional exposure summaries				
Metric	*Description*			
MAV_TH1	Arithmetic mean	0.77	0.59	0.09
MGAV_TH1	Geometric mean	**0.96**	0.13	0.11
M_MEDIAN	Median	**0.94**	0.08	0.03
M_95	95th percentile	0.42	**0.78**	0.13
M_STD	Standard deviation	0.28	**0.93**	0.01
Variance explained by each factor axis		4.22	2.81	1.42

*The principal component axes were rotated using the Varimax method; traditional and non-traditional measures of exposure were analyzed simultaneously.
[a]Average calculated with the denominator being the total time period not the total time above threshold.

TABLE 9. Correlation Matrix of Selected Magnetic Field Metrics* and Traditional Measures of Magnetic Field Exposure among Ontario Electric Utility Workers

	LAG_M_5	NGAV_TH8	MAV_TH1	MAV_TH10	MGAV_TH1	M_AVTRAN	M_MEDIAN	M_95	M_STD
LAG_M_5	1.00								
NGAV_TH8	0.05	1.00							
MAV_TH1	0.15	0.80	1.00						
MAV_TH10	−0.10	0.19	0.30	1.00					
MGAV_TH1	0.13	0.89	0.81	0.13	1.00				
M_AVTRAN	−0.27	0.07	0.01	0.10	−0.13	1.00			
M_MEDIAN	0.10	0.85	0.78	0.12	0.92	−0.08	1.00		
M_95	0.16	0.51	0.84	0.25	0.48	0.07	0.42	1.00	
M_STD	0.06	0.44	0.76	0.59	0.39	0.14	0.34	0.83	1.00

*A description of the variable names used to represent the metrics can be found in Table 1.

tify a series of metrics that satisfy the first two conditions.

The third condition was addressed by taking into account findings from biological studies of EMF. These suggest that relevant aspects of exposure include (1) measures of central tendency, (2) threshold or peak exposures, (3) duration of exposure above a threshold and (4) intermittent exposures. In the final selection of our subset of metrics, we have selected EF and MF exposures so as to address these four aspects, and in addition, to satisfy the first two conditions of a strong predictor variable as outlined in the previous paragraph.

Ideally, one would attempt to differentiate between case and control status using all possible metrics of exposure. For this study population, this would involve constructing cumulative lifetime exposure estimates using working histories. Performing such tabulations for 87 combined EF and MF indices of exposures that are dependent on both occupational group as well as site would clearly be quite onerous. Our analyses identify a manageable series of indices for which lifetime exposures can be constructed using a job exposure matrix.

The selection of a specific metric to represent exposures of central tendency is somewhat subjective. Our analyses suggests the consideration of three such indices: the arithmetic mean, the geometric mean and

TABLE 10. Mean Daily Exposure (in μT) for Traditional Measures of Magnetic Fields, by Occupational Group, Ontario Electric Utility Workers

Occupational group	Arithmetic mean	Geometric mean	Median	Standard deviation	95th Percentile
Clerk	0.269	0.189	0.212	0.478	0.581
Control maintainer	0.567	0.198	0.202	1.323	1.752
Customer service representative	0.202	0.090	0.106	0.513	0.734
Foresters	0.279	0.074	0.084	0.968	0.913
Inspector	0.174	0.073	0.078	0.360	0.633
Meter reader	0.162	0.079	0.092	0.350	0.411
Operators	1.614	0.752	1.146	2.117	3.862
Powerline maintainer	0.575	0.214	0.232	1.473	2.176
Professional and manager	0.210	0.124	0.137	0.350	0.560
Power maintenance electrician	1.097	0.458	0.518	2.587	4.797
Stockkeeper	0.246	0.156	0.210	0.441	0.501
Supervisor–tech & trade	0.254	0.141	0.169	0.490	0.663
Truck driver	0.138	0.078	0.085	0.253	0.470
Maintenance and security	0.762	0.257	0.276	1.537	2.951
Technical–other	0.310	0.185	0.224	0.535	0.767
P&C Technician	1.244	0.515	0.620	2.250	4.019
Trade–general	0.596	0.192	0.204	1.597	2.157
All groups	0.561	0.242	0.298	1.136	1.752

TABLE 11. Principal Component Analyses* of Selected Magnetic Field Metrics and Traditional Measures of Exposure among Ontario Electric Utility Workers with High Exposures

		Axis #1	Axis #2	Axis #3
Non-traditional exposure summaries				
Metric	*Description*			
MTD8_5	Percentage of time at or above 0.8 μT	0.42	0.17	0.60
LAG_M_5[a]	Autocorrelation at a 5 min lag	0.01	0.13	**0.85**
NGAV_TH8	Geometric mean of magnetic field at or above 0.8 μT	**0.96**	0.18	−0.08
NTD10_5[a]	Average of values at or above 3 μT for at least 5 min	0.86	0.42	0.13
MAV_TH10	Arithmetic mean of magnetic field at or above 3 μT	0.10	0.78	−0.05
M_AVTRAN	Average magnetic field transition in number of bins for adjacent samples	−0.07	0.41	**−0.64**
Traditional exposure summaries				
Metric	*Description*			
MAV_TH1	Arithmetic mean	0.88	0.43	0.13
MGAV_TH1	Geometric mean	**0.96**	0.10	0.17
M_MEDIAN	Median	**0.95**	0.10	0.08
M_95	95th percentile	0.62	**0.66**	0.16
M_STD	Standard deviation	0.40	**0.86**	0.07
Variance explained by each factor axis		4.99	2.40	1.60

*The principal component axes were rotated using the Varimax method; traditional and non-traditional measures of exposure were analyzed simultaneously.
[a]Average calculated with the denominator being the total time period not the total time above threshold.

the median. All three are correlated with the same factor axis and are highly intercorrelated, therefore, there is no need to retain all three. The retention of the arithmetic mean could be rejected based on several arguments. First, it is less correlated with the first factor axis than is the geometric mean and median. Secondly, when PCA was performed by occupational group, this metric did not always fall on the same factor axis that was representative of the geometric mean and median. Finally and perhaps most importantly, the arithmetic mean is more sensitive to skewed data (i.e. peaks and thresholds). As an index representing threshold mea-

TABLE 12. Correlation Matrix of Traditional Electric and Magnetic Field Exposures among Ontario Electric Utility Workers

	Electric Field Metrics				
Magnetic field metric	Arithmetic mean	Geometric mean	Median	95th Percentile	Standard deviation
Arithmetic mean	0.340	0.190	0.185	0.318	0.327
Geometric mean	0.248	0.239	0.223	0.208	0.202
Median	0.144	0.141	0.138	0.117	0.114
95th percentile	0.375	0.156	0.151	0.415	0.417
Standard deviation	0.308	0.115	0.110	0.332	0.399

sures will be kept, the rationale for also retaining the arithmetic mean is weak. The median and geometric mean were highly correlated with the same factor axis for all the occupational groups for magnetic exposures and all but one for electric field exposures. The effect of selecting one over the other on subsequent risk estimation would be negligible.

The standard deviation was highly correlated with the second factor axis for both EF and MF exposures. This metric was also poorly correlated with both the geometric mean and median. Knowledge of both the central tendency and spread of the data is essential in describing the distribution of exposure data. For these reasons, the retention of the standard deviation as a suitable metric in further risk estimation can be justified.

In addition to the standard deviation, the 95th percentile for magnetic fields and the average of MF at or above 3 μT , which are representative of peak or threshold measures, was correlated with the second factor axes. Although PCA would suggest that both metrics need not be used in further analysis, the correlational matrix revealed that these threshold measures were not highly correlated with any of the other metrics, except the arithmetic mean, and weakly correlated with the standard deviation. In addition, in order to account for one of the biologically plausible aspects of exposure as previously detailed it would be desirable to retain a threshold measure. The same logic could be applied to justify retaining the threshold exposure metric of arithmetic mean of EF at or above 2500 V/m in addition to the standard deviation.

Suitable candidates to represent intermittent exposures are average EF and MF transition in number of bins. This can be justified by the fact that these two metrics are correlated with the third factor axis and were poorly correlated with the other metrics. Using the same rationale one could justify retaining autocorrelations at 5 min lags (EF and MF). However, it is worth noting that the overall proportion of variance explained by the third factor axes is relatively small for both EF and MF ($<$20%).

Our findings are consistent with previous analyses of indices of MF that revealed high intercorrelations between the geometric mean, mean and fractions of measurements exceeding 0.5 and 1.0 μT [Sahl et al., 1994]. The authors also found the series of metrics consisting of arithmetic mean, 95th percentile and fractions of measures exceeding 5 and 10 μT accounted for a significant portion of the variability of exposure data as did a factor axis representative of the standard deviation and fraction of measures $>$ 100 μT.

For EF and MF, Armstrong found high correlations between the time weighted average (TWA) and summaries of peak exposures [Armstrong et al., 1990]. This led them to conclude that the use of the arithmetic mean as a summary measure would serve as a reasonable proxy for assessing peak exposures. The arithmetic mean is also desirable as it avoids the arbitrary choice associated with indices representing peaks or thresholds. With our data, if analysis were restricted to one measure of exposure, it would be desirable to rely on the arithmetic mean. This could be justified by the fact that the arithmetic mean is correlated, albeit weakly, to measures which are highly correlated with the first two factor axes, specifically, the median geometric mean and the standard deviation. However, in a distribution that is not highly skewed, the arithmetic mean will be less effective in identifying effects that are related to threshold or similar types of measure. Consequently, by only using the arithmetic mean we may miss capturing potential biological effects associated with low threshold exposure summaries.

Our findings of a weak correlation between indices of electric and magnetic fields are consistent with previous findings [Armstrong et al., 1990; Savitz et al., 1994]. Savitz and colleagues found higher EF and MF correlations among occupational groups than for person days and led to the conclusion that a single measure of central tendency appears to be adequate when exposures are assessed at the level of job title. Conversely, recent analysis has demonstrated the relevance of magnetic field indices other than average field strength in the assessment of occupational exposure of electric utility workers [Zhang et al., 1997]. This previous study found that although average field strength was able to distinguish between high and low exposed occupational groups it poorly discriminated exposures between highly exposed groups [Zhang et al., 1997]. Our PCA suggested that measures of central tendency explained most of the exposure variability for the majority of the occupational groups. However, the number of principal component axes for the 17 occupational groups ranged from two to four suggesting that measures of central tendency, by themselves, may not adequately account for the variability of MF and EF exposures within occupational groups.

The use of the series of metrics selected from these analyses to estimate cancer risk in the cohort of Ontario electrical utility assumes the exposure measures are representative of the much larger cohort. It should also be noted that the observed correlations between the indices may not be representative of historical exposures. However, historical corrections for the arithmetic and geometric means of EF and MF had a non-significant effect on estimates of the odds ratios for all cancers [unpublished tabulations].

The measurement of electric fields is inherently more difficult than for magnetic fields. At any point in time, the electric field measurement made using a personal monitor is influenced by (i) the wearing location, (ii) the magnitude and direction of the local ambient electric field, the (iii) posture of the body, (iv) and, to a lesser extent, the extent to which the worker is grounded. The type of clothing generally has little or no effect on the measurements (unless the monitor is worn under wet clothing). In our study we required that the workers carry the monitor on a waist belt, except when wearing a harness for work at elevation, in which case the monitor was attached to the front strap of the harness. By having each worker wear the monitor 7–8 h each day for 5 days, we obtained an average measurement for the variety of body postures and electric field environments normally encountered during the execution of the majority of routine tasks. To account for the variation in job tasks that occur seasonally, members of relevant trade groups were monitored throughout the year. Therefore, by specifying the wearing position of the monitor and sampling many workers in each occupational group for entire workdays, we believe that the electric field average exposures can be used to quantify the relative exposures of these groups. The range of EF and MF mean exposure levels (Tables 6, 10) suggests that the ability to separate occupational groups is at least as great for electric fields than for magnetic. However, stratification of specific occupational groups by work location revealed fewer significant differences between sites for electric fields than for magnetic fields.

Further research should be undertaken to determine which metrics best differentiate those workers who develop cancer compared to those who do not. Brain cancer and haematological malignancies warrant particular attention. This study identifies a series of metrics that serve as a starting point for such a discriminant analysis in this cohort. For EF, a suitable series of metrics would consist of the geometric mean, the standard deviation, autocorrelation at 5 min lags, the arithmetic mean of exposure at or above 2500 V/m and the average electric field transition in number of bins. Similarly for MF, an appropriate series of metrics would consist of the geometric mean, the standard deviation, autocorrelation at 5 min lags, the average mean of exposure at or above 3 µT, and the average magnetic field transition in number of bins. When examining the influence of multiple exposure indices on various forms of cancer, one should be wary of the dangers of multiple testing.

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