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Temporal Characteristics of Transmission-Line Loadings in the Swedish Childhood Cancer Study

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A recent study conducted in Sweden reported that 1) leukemia risk in children who lived near 220 or 400 kV electric-power transmission lines was associated with calculated historical magnetic field levels; 2) children living within a distance of 50 m of transmission lines had an elevated risk of leukemia; and 3) there was no association between leukemia and residential magnetic fields measured many years after diagnosis. Subsequently, these investigators found through logistic regression analysis that disease was more strongly associated with calculated historical fields than with distance. Since the calculated historical fields in that study depended predominantly on distance and transmission-line load current, the logistic regression results suggest that historical load current plays an important role in the epidemiological results. Thus, we studied hourly 1974 load-current data for six transmission lines, and we examined 1958-1985 annual load-current data for 112 transmission lines. Most lines exhibited marked diurnal load-current rhythms during 1974, and all six showed systematic weekday–weekend differences. During 1958–1985, average loadings of Swedish 220 and 400 kV lines increased by about 1.3% year. Predictive-value and kappa-statistic analyses indicated that Swedish transmission-line load currents were not stable over long periods, so that contemporaneous load current (or a contemporary magnetic field measurement) was not a good surrogate for historical load current (or historical magnetic fields). The results provide a potential explanation of the failure of the Swedish Study to find an association between leukemia and contemporaneous magnetic field levels measured many years *after* the etiologic period, and suggest that the inclusion of load-current data could significantly improve the quality of historical field calculations. Bioelectromagnetics 19:354–365, 1998.

Key words: childhood leukemia; Swedish study; magnetic fields; exposure assessment

INTRODUCTION

Several epidemiologic studies have reported associations between childhood cancer and the configurations of electric power wiring located near subjects' homes [Wertheimer and Leeper, 1979; Savitz et al., 1988; London et al., 1991]. The most frequent interpretation of these results is that they reflect an underlying association between childhood cancer and exposure to power-frequency magnetic fields [Wertheimer and Leeper, 1979; Savitz et al., 1988; London et al., 1991; Kaune, 1993]. This interpretation is supported by measurements showing that magnetic field levels are larger, on the average, in high-current-configuration homes (HCC) than in low-current-configuration (LCC) homes [Kaune et al., 1987; Barnes et al., 1989; Zaffanella, 1993]. On the other hand, the failure of several studies [Savitz et al., 1988; London et al., 1991] to find stronger or even comparable associations between disease status and directly measured magnetic field levels in homes of case and control subjects has raised doubts that there is a causal relation between exposure to power-frequency magnetic fields and cancer risk in children.

In case/control studies, cases can be identified for study only after they have contracted the disease of interest. Thus, the exposure that is being studied as a

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potential cause of the disease is always historical, that is, has already occurred at the time the study is actually conducted. Historical exposure assessment presents a significant problem for epidemiological studies of power-frequency magnetic fields. The studies described in the preceding paragraph assumed that contemporaneous wire codes and magnetic field measurements could be used as surrogates for historical magnetic field exposure. There is, however, little evidence with which to evaluate this assumption. A recent study performed by Feychting and Ahlbom (1993, 1994), commonly known as the Swedish Study, attempted to overcome this difficulty by concentrating on a population for which quantitative historical calculations of magnetic field exposure could be made. The Swedish Study covered both children and adults. Of the various results from this study, the ones that are strongest and have received the most attention concern childhood leukemia [Feychting and Ahlbom, 1993]. For this reason, the analyses presented in this paper are restricted to the subjects of the childhood leukemia portion of the Swedish Study.

In the Swedish Study, most children (age < 16 y) in Sweden were studied who had lived within 300 m of 220 and 400 kV electric power transmission lines sometime during the period 1960–1985. Disease status was assessed through linkage to the Swedish Cancer Registry. Typically, four matched control subjects were selected for each case [Feychting and Ahlbom, 1993]. Exposure assessment had several components. First, spot magnetic field measurements were made in the homes inhabited by case and control subjects at the time of diagnosis of the case. Second, at the same time when the spot measurements were made, the power company (electric utility) that operated the transmission line(s) passing close to the home under study was telephoned and line load-current data (i.e., line current in amperes) were obtained. These data, along with information on power line/home geometry, were used to calculate magnetic fields at the time of the spot measurements using a computer program developed by the Swedish State Power Board.

The final component of the exposure assessment for the Swedish Study utilized historical load-current data for the power lines that passed close to the homes occupied by case and control subjects to calculate annual average magnetic fields for the etiologically relevant time, defined as the year closest to diagnosis when the case had lived within 300 m of a transmission line. This component was feasible in the Swedish study because detailed load records had been kept for most 220 and 400 kV transmission lines.

Feychting and Ahlbom found that distance between nearby power lines and the homes of subjects was associated with leukemia incidence in children in their study population. Since the wiring configuration system of Wertheimer and Leeper (1982), when applied to *transmission* lines, is based solely on distance, this finding seems consistent with earlier observations of associations between wiring configuration and childhood leukemia [Wertheimer and Leeper, 1979; Savitz et al., 1988; London et al., 1991]. Furthermore when the contemporaneous spot magnetic field data were examined, no association with disease status was observed, again consistent with earlier studies. However, when historical calculated magnetic fields were used as the measure of exposure, an elevated risk (risk ratio of 2.7, 95% confidence interval extending from 1.0 to 6.3) of contracting leukemia was observed in children with calculated magnetic fields ≥ 0.2 μT compared with children with fields < 0.1 μT. Thus, the results of the Swedish Study support the hypothesis that the inability of earlier studies [Savitz et al., 1988; London et al., 1991] to find a stronger association between measured magnetic fields and disease status occurred because contemporaneous spot magnetic fields are a poor surrogate for historical magnetic fields.

In epidemiological research, power-frequency magnetic fields have most often been characterized by their ''resultant'' magnitudes. In terms of measured or calculated vector components of a magnetic field (B_x, B_y, and B_z), the resultant field strength, B, can be calculated using the formula $B = \sqrt{B_x^2 + B_y^2 + B_z^2}$. Resultant magnetic fields produced by power lines depend on three parameters: line current (I), line geometry, and the distance (R) from the power line to the point where the field is being calculated. For single-circuit transmission lines carrying ''balanced'' currents (i.e., all three phase currents equal in magnitude and offset from each other in phase by ±120°), this relation is [Kaune and Zaffanella, 1992]

$$B = \alpha \frac{IS_{\mathrm{RMS}}}{R^2}, \quad R \gg S_{\mathrm{RMS}}, \tag{1}$$

where B has units of tesla (T), $\alpha = 0.245\ \mu\mathrm{T} - \mathrm{m/A}$, S_{RMS} is the root-mean-square distance between the three conductors of the power line (i.e., $S_{\mathrm{RMS}} = \sqrt{(S_{12}^2 + S_{13}^2 + S_{23}^2)/3}$, S_{ij} = transverse distance between the i^{th} and j^{th} phase conductors in meters), and R has units of meters.

Even when $R \gg S_{\mathrm{RMS}}$, the accuracy of Equation (1) is limited by its assumption of balanced phase currents and its neglect of stray currents induced in the ground and in overhead shield wires that may be present to protect the line under consideration from lightning strikes (IEEE, 1988). Imbalance in the magnitudes of the currents on transmission lines is usually fairly small. So long as imbalance does not result in the generation of a ''net'' current on the line (i.e., a current that travels in one direction on the line but is returned through other routes, such as the ground), effects on the magnetic field produced by the line will be small. If a net current is produced, the magnetic field attributable to it will be proportional to $1/R$ and, thus, will decay with distance less rapidly than the field component expressed by Equation (1). Consequently, when R is sufficiently large, the net-current component of the field will come to dominate and Equation (1) will no longer be an approximation to the actual field strength. However, this usually occurs at distances from the power line where B is already rather small [EPRI, 1982; Swanson, 1995], less than about 0.1 μT. Consequently, Equation (1) can serve as a guide to the magnetic fields produced by a transmission line at distances extending from the edge of its right-of-way out to distances where B has declined to about 0.1 μT.

Since the calculated magnetic field, B, depends on R in Equation (1), we would expect a substantial association between the two, which means that an underlying association between disease and B (or R) would have to produce a secondary association between disease and R (or B). It is, therefore, understandable that Feychting and Ahlbom found an association between *both* distance and calculated historical fields, but it was not clear from their initial work which of these parameters was the more fundamental measure of exposure and which was secondary.

Additional analysis of the childhood leukemia data was presented in a second paper [Feychting et al., 1996] in which a logistic regression was performed on the childhood leukemia data with both R (distance, categorized as ≤ 50 m, 51–100 m, or >100 m) and B_H (calculated historical magnetic fields, categorized as < 0.1 μT, 0.1–0.199 μT, or ≥ 0.2 μT) included as independent variables. The results of this analysis suggested that the association between disease and B_H was primary because controlling for B_H eliminated the association between disease and R, while controlling R left the association with B_H largely unaffected.

The present paper begins by examining the statistical relation among calculated historical magnetic fields (B_H), distance (R), and transmission-line loads (I). The goal of this analysis is to determine the relative contributions of R and I to B_H. This analysis shows that the majority of the between-subject variability in B_H is due to R, with I playing a lesser role in this regard. Even so, as noted above, the work of Feychting et al. (1996) indicates that B_H is more strongly linked to leukemia than R, suggesting that I plays an important role in the epidemiological findings. Therefore, the remainder of this paper examines data on transmission line loadings in Sweden to determine the temporal behavior, over durations extending from days to years, of this parameter.

TRANSMISSION LINE LOAD: CURRENT DATA

Hourly Transmission-Line Load-Current Data

We obtained hourly load-current data for three 400 kV and three 220 kV Swedish transmission lines for the entire year of 1974. In the 1970s and earlier years, electric power in Sweden was predominantly produced by hydroelectric generating stations located in northern Sweden. The population in Sweden is located primarily in the southern part of the country, so an extensive grid of transmission lines was required to connect the two parts of the country. The six lines for which we were able to obtain load-current data were part of this grid and were also included in the leukemia study.

The movement of electric power in transmission lines is characterized, at any moment in time, by the real and reactive powers, normally measured in units of megawatts (MW) and megavolt-amperes reactive (MVAR). The 1974 hourly data for our study were acquired using cumulative power meters inserted in the six transmission lines. Each meter actually consisted of a tandem pair. The first meter accumulated real and reactive power data for 1 h; it was then stopped and the second was started. At the end of the second hour, the second meter was stopped and the first started again. Technicians manually recorded and reset meter readings each hour. Four quantities were actually measured for each transmission line: the real and reactive energies moving in one direction on the line (called the ''to'' direction) and the real and reactive energies moving in the opposite (the ''from'') direction.

In this paper, we shall refer to the six transmission lines for which we have hourly load-current data as Line #1 through Line #6. Lines #1, #2, and #3 operated at a nominal voltage of 400 kV while lines #4, #5, and #6 were at 220 kV. No line had complete data for all of 1974. Line #4 was missing only 1 h of data while, at the other extreme, Line #6 was missing 21 days of data.

During our initial review of the data, we identified two potential outlier points. By comparison with data for surrounding hours, we determined that these points were either in error (which would not be too surprising since the data were recorded manually), or were the result of some unusual operating condition (e.g., a fault on a nearby transmission line). In either case, we concluded that these two values were not representative of normal line conditions, so they were deleted.

Real, reactive, and total hourly average transmission line currents were estimated from the hourly real and reactive energies using the formulas

$$I_{\mathrm{MW}} = 1000\,\frac{(MWh_{\mathrm{To}} + MWh_{\mathrm{From}})}{\sqrt{3}\;V}\,,$$

$$I_{\mathrm{MVAR}} = 1000\,\frac{(MVARh_{\mathrm{To}} + MVARh_{\mathrm{From}})}{\sqrt{3}\;V}\,,\quad \text{and}$$

$$I = \sqrt{I_{\mathrm{MW}}^2 + I_{\mathrm{MVAR}}^2}\,, \tag{2}$$

where I_{MW} is the average real current in amperes (A), I_{MVAR} is the average reactive current, I is the total current, MWh_{To} and MWh_{From} are the cumulative hourly real energies in the to and from directions (both positive numbers), $MVARh_{\mathrm{To}}$ and $MVARh_{\mathrm{From}}$ are the cumulative hourly reactive energies in these directions (both positive numbers), and V is the phase-to-phase voltage in kV. The factor of 1,000 appearing in the first two formulas of Equation (2) is included so that the calculated currents are in units of amperes.

Annual Average Transmission-Line Load-Current Data

During the data acquisition phase of the original Swedish Study, annual average load-current data were obtained for 112 transmission lines with voltages of 220 and 400 kV. Data were obtained for the period 1958–1985. Not all lines had data for every year since many (51) were constructed after 1958. Also, the 1984 and 1985 data for 70 lines were not acquired. The duration of data for the average line was 20.8 y. Fourteen lines had less than 10 y of data, 25 had between 10 and 20 y of data, and 73 had more than 20 y of data.

Average annual loads of most power lines were obtained by averaging detailed records of hourly load current kept by Swedish electric companies [Feychting and Ahlbom, 1993]. For a few lines, hourly data were not available and annual average loads were estimated by considering their locations within the larger electric power transmission system in Sweden and using data for neighboring transmission lines [Feychting and Ahlbom, 1993]. All annual average transmission loads were rounded to the nearest 100 of amperes.

RESULTS

Calculated Magnetic Fields, Distance, and Load Currents

Equation (1) expresses the relation between a calculated resultant magnetic field (B), distance (R), and load current (I) for single-circuit transmission lines, assuming that the currents in all conductors are equal in magnitude and differ in phase by ±120°. These conditions of current balance were assumed for all the field calculations made in the original Swedish study, and thus Equation (1) can be applied directly to the 82% of the childhood subjects in the Swedish Childhood Leukemia Study who lived close to single-circuit power lines. For the remaining 18% who lived close to double-circuit lines, or to multiple single-circuit lines, Equation (1) can still be approximately applied if I is selected to be the load current of the circuit that contributes most strongly to B. (Evidence for the effectiveness of this approach to handling multi-circuit situations is forthcoming.)

Figure 1 shows scatter plots relating the *calculated* historical magnetic field to distance for case and control subjects of the Swedish Childhood Leukemia Study. Both linear and logarithmic plots are shown; note that the abscissa is $1/R^2$ for the linear plot and R for the other. There is clearly a linear trend in both plots, which is not surprising since the data being plotted were originally calculated using computer methods that reduce to Equation (1) when R is large with respect to the distance between adjacent conductors, an assumption that was essentially always satisfied in the Swedish dataset. There is, however, considerable scatter about the linear trend line. This scatter presumably stems from the additional dependence of the calculated magnetic fields on line geometry and line current. To quantify the relative importance of R and I in the determination of B_{H}, we performed a regression analysis using the two models

$$\left.\begin{aligned} B_{\mathrm{H}} &= b_0 + b_1 I/R^2 + \varepsilon \\ B_{\mathrm{H}} &= b_0 + b_1'/R^2 + \varepsilon \end{aligned}\right\} \tag{3}$$

where the constants b_0 and b_1, and b_1' were adjusted to minimize the residual variability, ε. (In these equations, the units of B_{H}, I, R, b_0, b_1, and b_1' in the second are μT, A, m, μT, $\mu\mathrm{T} - \mathrm{m}^2/\mathrm{A}$, and $\mu\mathrm{T\text{-}m}^2$, respectively.) The results of this fitting process are summarized in Table 1. Note that 96% of the between-subject variability in calculated historical magnetic fields was explained by the model that involved *both* distance and load current (the top line of Equations 3). When load current was excluded from the analysis [bottom of Equations (3)], 59% of the between-subject variability was explained by the model that involved *only* distance (bottom line of Equations 2). We may, therefore, conclude that the majority of between-subject variability is explained by distance while load current plays a

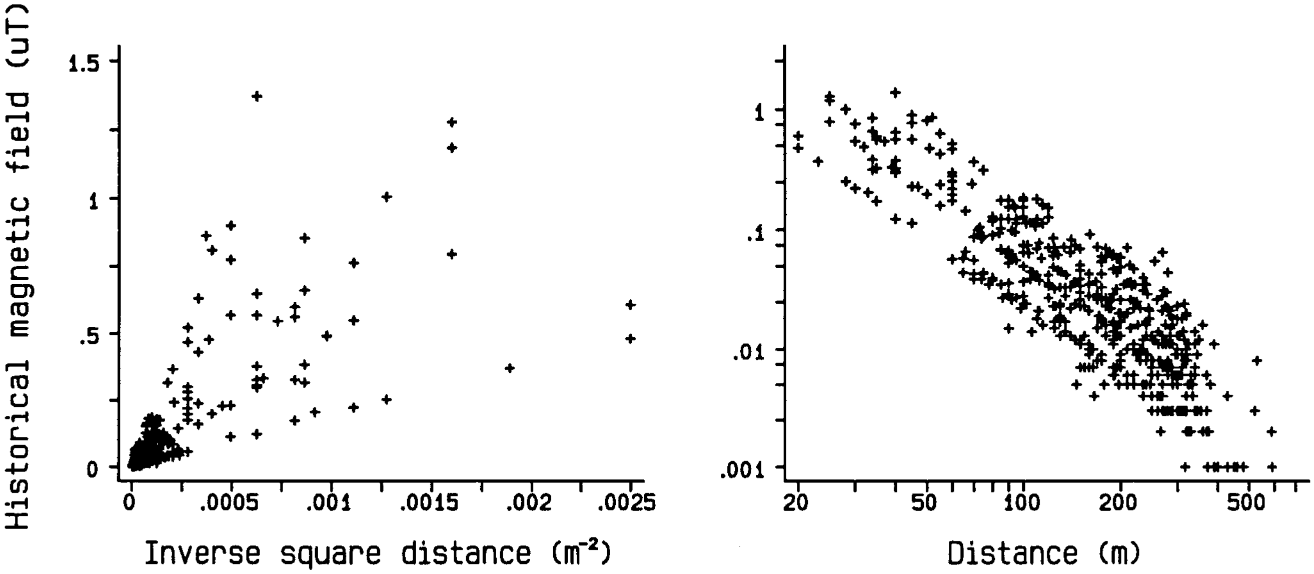

Fig. 1. Scatter plots showing relation between calculated historical magnetic fields and inverse-square distance (left plot) or distance.

lesser, but still substantial, role in this regard. Since Equation (1), a single-circuit model that involved only *I* and *R*, explained nearly all the between-subject variability, differing powerline geometries and the presence of other circuits was evidently of little importance in this dataset.

Analysis of Hourly Transmission-Line Loads

Table 2 presents summary statistics characterizing minimum, mean, and maximum annual total, real, and reactive load currents carried by the six Swedish transmission lines for which we have hourly load data. Annual mean 1974 currents vary from 719 A (Line #1) through 103 A (Line #6). Mean reactive load currents were substantially less than mean real load currents.

We first isolated the daily and weekly rhythms in transmission-line loads from longer-duration variations (e.g., seasonal rhythms) using the following technique. We separated the data of each line into 52 separate records, each corresponding to one calendar week (Monday–Sunday) in 1974. We then dropped records containing missing data, leaving 49 weeks of data for Lines #2 and #3, 48 weeks for Line #1, 45 weeks for Line #6, and 44 weeks for Lines #4 and #5. We normalized each week's load-current data, consisting of 168 individual values corresponding to the total hours in a week, by dividing each load current value by the mean of all values, that is, we normalized each week's load current to a mean of 1. We then combined the data for each transmission line across all weeks by calculating the mean of the normalized loads for the first hour of all weeks, the second hour of all weeks, and so on. The results are shown in Figure 2.

Line #1 exhibits a distinct diurnal rhythm that varies between weekdays and weekends. Figure 3 shows the diurnal rhythms separately for the aggregate of the weekday and the weekend data for this line. On weekdays, mean transmission-line load current was lowest during the night, from about 0 to 600 h. It rose to a peak at 800–1000 h, and then slowly declined through the remainder of the day until about 2000 h, when it dropped fairly quickly to the night-time lows.

TABLE 1. Results of Regression Analysis of Calculated Historical Magnetic Fields (B_H), Distance (R), and Load Current (I)

	Parameter estimates		Sum of squares		
Model	$b_0 \pm$ SE[a]	b_1 (b_1') $\pm$ SE[a]	Model	Residual	r^2
$B_H = b_0 + b_1 I/R^2$	(0.003 ± 0.005) μT	(2.49 ± 0.02) μT-m^2/A	14.54	0.66	0.96
$B_H = b_0 + b_1'/R^2$	(0.20 ± 0.005) μT	(468 ± 17) μT-m^2	8.94	6.26	0.59

[a] SE = standard error.

TABLE 2. Annual 1974 Summary Statistics for Total, Real, and Reactive Line Currents Carried by Six Swedish Transmission Lines

Line	Voltage class (kV)	Total line current (A)			Real line current (A)			Reactive line current (A)		
		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
1	400	23	719	1,194	23	704	1,193	0	117	438
2	400	2	321	832	0	316	832	0	46	190
3	400	11	282	634	0	262	632	1	80	203
4	220	8	173	358	0	146	356	2	69	233
5	220	0	187	469	0	181	464	0	37	104
6	220	0	103	294	0	83	293	0	44	120

On the weekends, the diurnal rhythm was similar, but the rise that occurred during the day was much less marked, probably because of lower levels of weekend commercial activity.

Weekly load current rhythms were similar for Lines #1, #2, and #5 (Fig. 2). Line #3 exhibited a pronounced diurnal rhythm, with a smaller weekday–weekend difference than observed with Lines #1, #2, #4, and #5. Line #4 exhibited a definite, but comparatively weak, diurnal rhythm, with a more pronounced difference between weekdays and weekends. Finally, there appears to be little diurnal rhythm for Line #6, at least during weekdays. There does appear, however, to be a difference between weekdays and weekends.

We next removed the daily and weekly structure from the data to concentrate on its longer term behavior. The daily rhythm in the data was removed by replacing the 24 hourly values with their average. The weekday–weekend differences were then filtered out using a 7-day moving average algorithm [Chatfield, 1989]. The resulting 1974 total load currents for each transmission line are presented in Figure 4.

There is no obvious seasonal pattern visible to the eye in the six plots in Figure 4. To investigate further, we normalized the yearly data for each of the six transmission lines to a mean of 1. We then aggregated the data for each line into 12 monthly averages. Finally, we computed the means, by month, of the six transmission lines. The results (Figure 5) suggest that, on the average, loadings of the six transmission lines were higher in the first 3 months of the year than in the second 3 months. This difference was statistically

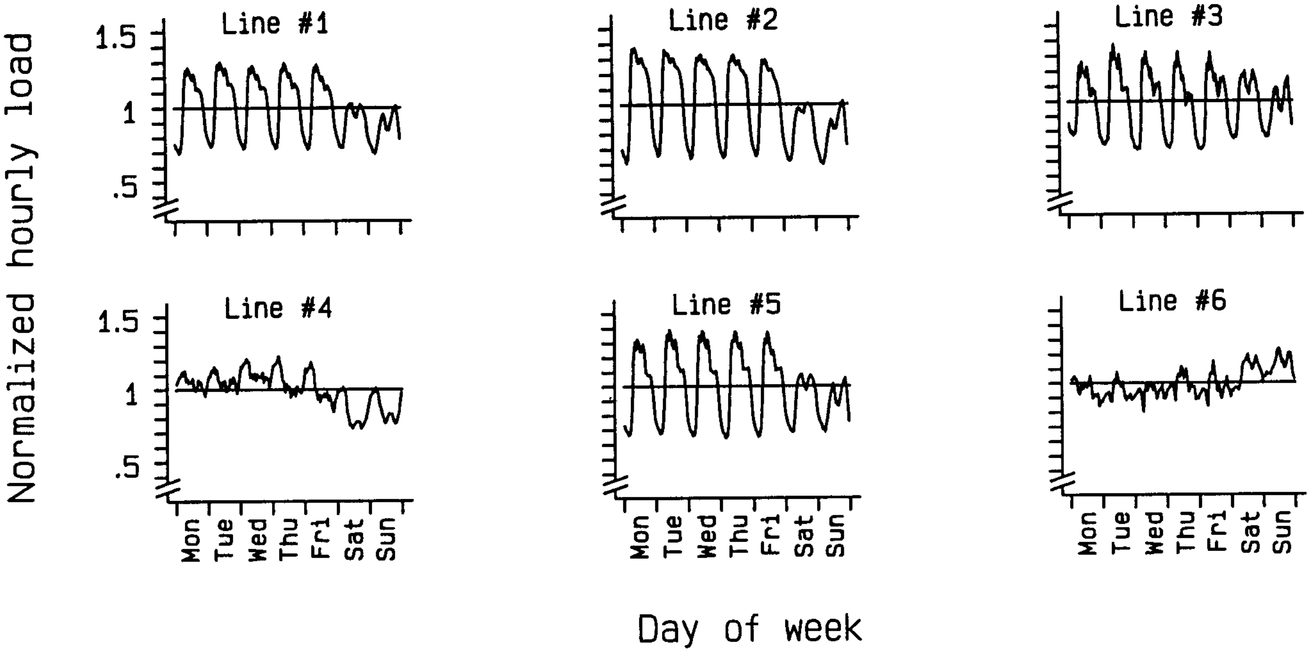

Fig. 2. Plots of hourly load currents, normalized to weekly means of 1 and aggregated across all weeks in 1974, showing diurnal and weekly rhythms.

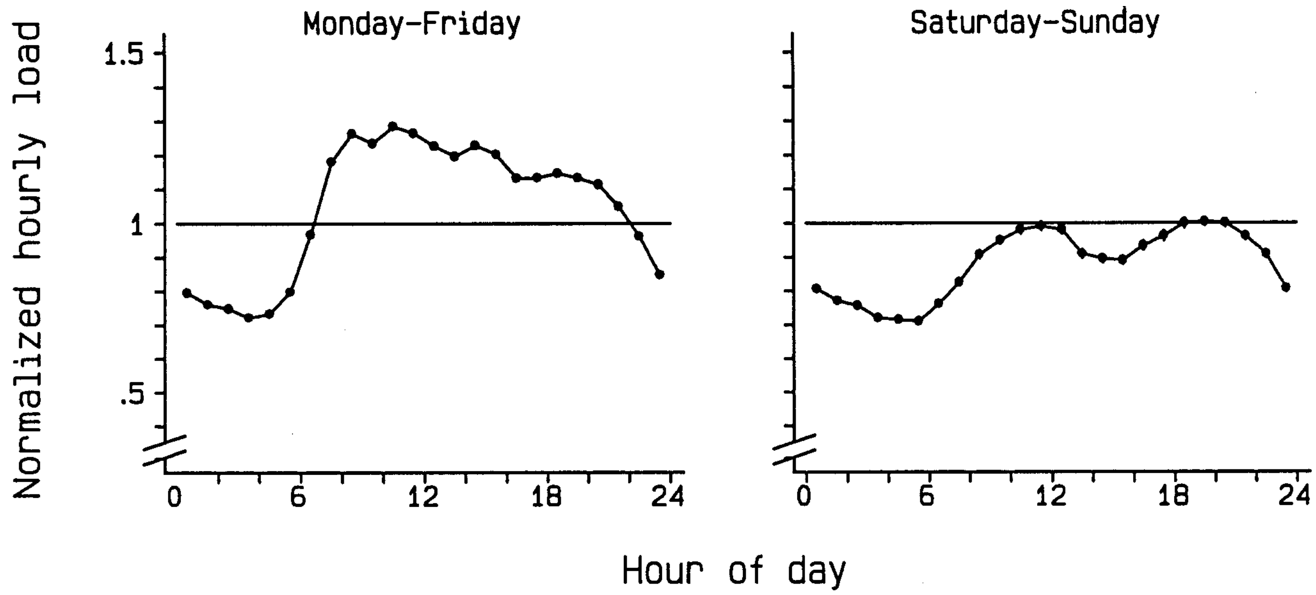

Fig. 3. Weekday and weekend diurnal rhythms of load currents carried by one Swedish transmission line during 1974. The current data were normalized so that the average for each week was 1, and the normalized values were then aggregated across all weeks.

significant (P = .0013, Kruskal-Wallis test) and probably reflected changing weather conditions. Average transmission loads climbed from June through August (P = .04). The September load current may have been lower than the August and October loadings, but the difference was not sufficiently consistent across lines to be statistically significant. In the absence of multiyear data, it must be regarded as unknown whether these remarks can be extrapolated to years other than 1974.

Analysis of Annual Transmission-Line Load-Current Data

As described earlier, we obtained annual average load-current data for 112 Swedish transmission lines covering the years 1958–1985 (not all lines have data for all of these years). The consumption of electricity by developed societies has tended to increase substantially over time. Thus, we expected the average transmission-line currents to have increased between 1958 and 1985. While analysis of the data showed this to be the case, the actual average increase per year was only about 3.8 A (about 1.3%/y), a relatively small amount. To obtain an idea of the numbers of transmission lines showing overall trends toward increasing or decreasing load current, we used a nonparametric trend test [Cuzick, 1985]. Thirty-five lines had a statistically significant trend to increasing load current, 15 had a statistically significant negative trend, and the remaining 62 exhibited no overall trend. (It is apparently a fairly common occurrence for the loadings of transmission lines to increase over time, until they near their design loadings, at which point a new line is constructed to relieve the demand on the original. After the new line is energized, the loading on the original one is reduced substantially, but then may start to increase again as demand for electric power continues to grow.)

We next characterized the temporal variation in transmission-line annual load current. For each of the 112 lines, we calculated the mean, standard deviation, maximum, and minimum loads for the years when the lines were operating. We then calculated two statistics to characterize overall temporal variability: CV, the coefficient of variation (standard deviation divided by mean); and D_{max}, the maximum deviation from the mean divided by the mean. Figure 6 shows a cumulative probability plot of these two statistics.

We then turned to the question of how strongly related were transmission loads during different years. We first calculated Pearson correlation coefficients between the 1983 annual load currents of the transmission lines (i.e., the annual loads during the most recent year for which we had complete data) and their load currents during earlier years. The results (Fig. 7) show that the correlation between average loads for years separated by 10 y or more was less than 0.6. For time separations of 15 y or more, the correlation was consistently about or less than 0.5.

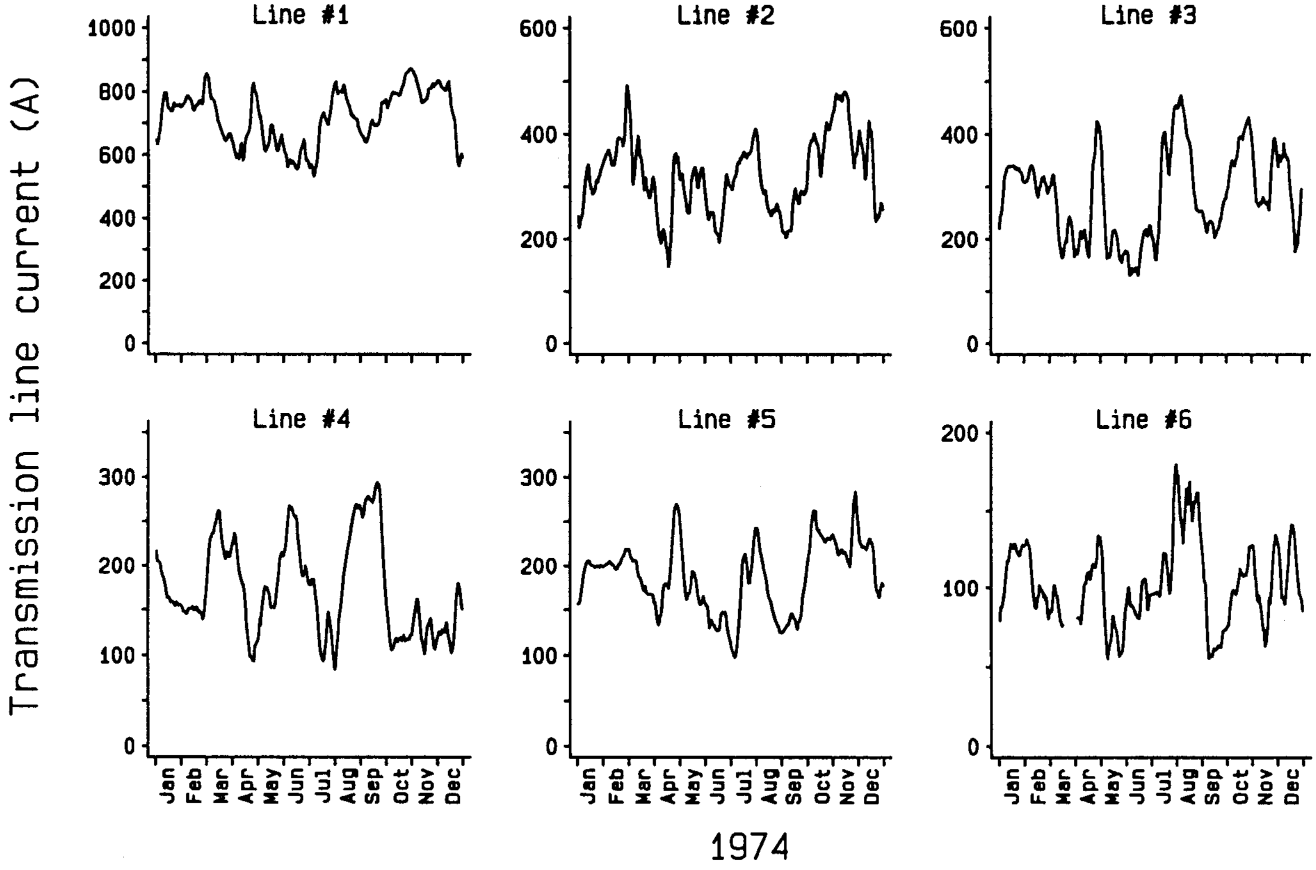

Fig. 4. Total load currents carried by six Swedish transmission lines during 1974. Data have been filtered to remove daily and weekly rhythms.

There are limits to correlational analysis in evaluating the association between surrogate and primary measures of some quantity when these quantities are categorized (as is usually done in epidemiological research). A battery of statistical techniques have been developed to characterize the relation between two categorical measures [Fleiss, 1981; Kleinbaum et al., 1982]. We first used ''predictive values'' to characterize the association between transmission-line loading during the most recent year for which data are available and during earlier years, that is, we characterized the ability of a ''contemporaneous'' transmission-line load current to predict load currents during earlier years, where load currents were categorized into high or low depending on whether I was greater than, or less than or equal to, a load current cut point I_0. We considered two cutoff load currents, 300 A and 400 A, corresponding, respectively, to the approximate median (50th percentile) and 70th percentile of all the transmission-line loading data.

The positive predictive value, η_+, for the 1983 load-current data (I_{1983}) to predict load currents at an earlier year (I_y) is the probability that I_y is high given that I_{1983} is high (i.e., the probability the true load current was high given that it was measured to be high). Similarly, the negative predictive value, η_-, is the probability that I_y is low given that I_{1983} is low. Figure 8 shows the calculated predictive values, as a function of the number of years prior to 1983, for load current cut points of 300 A and 400 A. In both cases, negative predictive values remain high, near 1, indicating that transmission lines with a low loading in 1983 tended to have low loads during earlier years. On the other hand, positive predictive values decreased steadily as the period of extrapolation was extended to earlier dates, indicating that transmission lines with high loadings in 1983 did not necessarily have high loadings in earlier years.

A second method for characterizing agreement between two categorical measures of a quantity is the kappa statistic [Fleiss, 1981]. This statistic measures the amount of agreement between the two measures under study in excess of that expected by chance alone. Thus, $\kappa = 0$ corresponds to agreement at chance levels

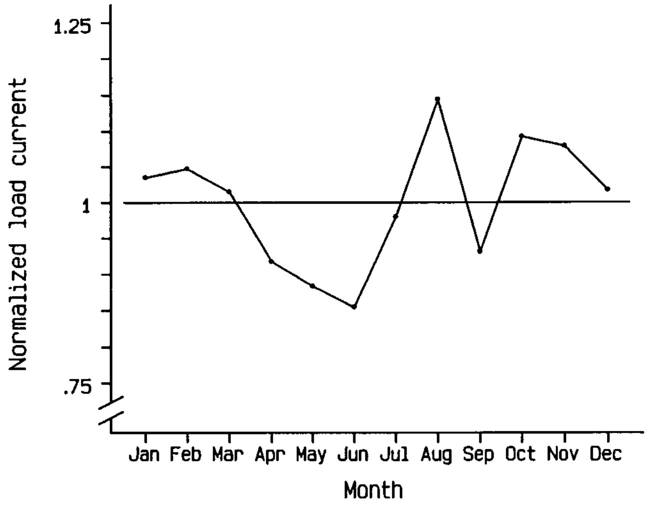

Fig. 5. Means of 1974 monthly average normalized load currents carried by six Swedish transmission lines.

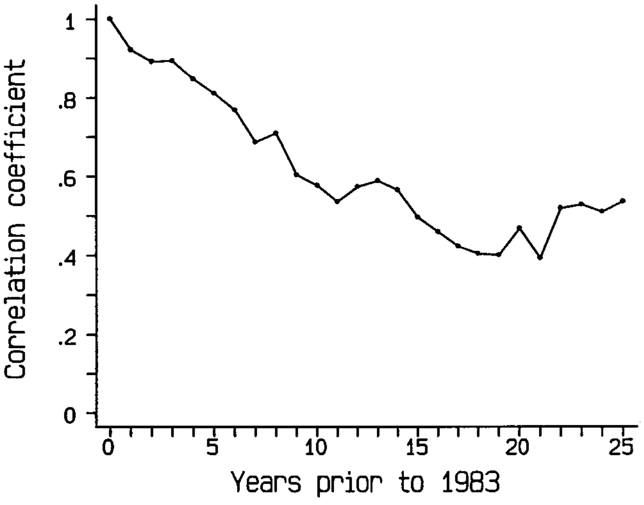

Fig. 7. Pearson correlation between 1983 annual-average loadings of 112 transmission lines and loadings during earlier years.

while $\kappa = 1$ means the two measures are in perfect agreement. The curves labeled ''Cut point = 300 A'' and ''Cut point = 400 A'' in Figure 9 show the kappa statistics for various time durations prior to 1983 assuming cut points of 300 A and 400 A were used to dichotomize exposure. During the first few years prior to 1983, agreement between the contemporaneous and historical measures was quite high. At 5 years, $\kappa = 0.69$ for the 300 A cut point and 0.61 for the 400 A cut. Extrapolating 10 years in the past yielded kappa values of 0.63 and 0.42 for the 300 A and 400 A cut points, respectively. At 15 years in the past, $\kappa = 0.45$ and 0.37 for these two cut points. At 20 years, these values declined to 0.35 and 0.29, indicating little agreement beyond that expected by chance alone.

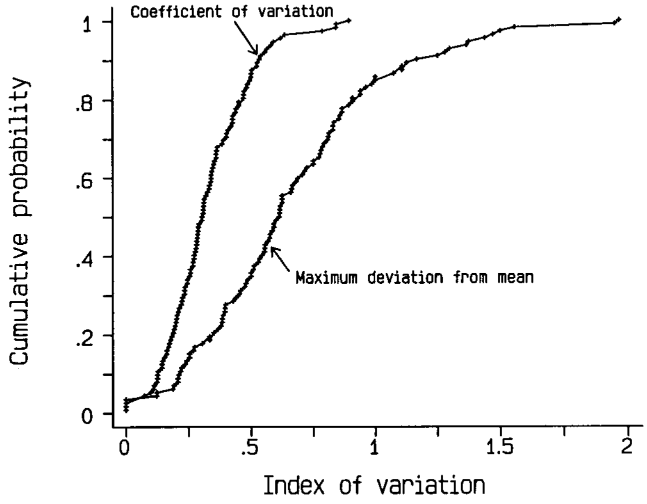

Fig. 6. Cumulative probability plots of the coefficients of variation and the maximum deviations from the mean of the annual load-current data of 112 transmission lines during the period 1958–1985.

DISCUSSION

The magnetic fields produced by a power line depend on line geometry, line current, and distance from the line. In this paper we showed that the calculated historical magnetic fields in the Swedish study depended most strongly on distance but also depended significantly on transmission-line load current. However, even though distance was the strongest determinant of the calculated historical magnetic fields, logistic regression analysis [Feychting et al., 1996] indicated that the association between disease and calculated historical fields was stronger than with distance. This result suggested that transmission-line load current plays an important role in the epidemiologic results of the Swedish Study. We thus examined available data for Swedish transmission lines to see what could be learned about the temporal pattern of their load current.

We first examined hourly load-current data for three 220 kV and three 400 kV Swedish transmission lines for the entire year of 1974. We found that five of the six lines exhibited a distinct daily diurnal rhythm in load current (Figs. 2 and 3). Weekend loadings on these five lines were lower than weekday loadings, presumably reflecting reduced levels of commercial activity on weekends. Interestingly, the weekend load current on the sixth line was slightly higher than on weekdays. The longer term behavior of transmission-

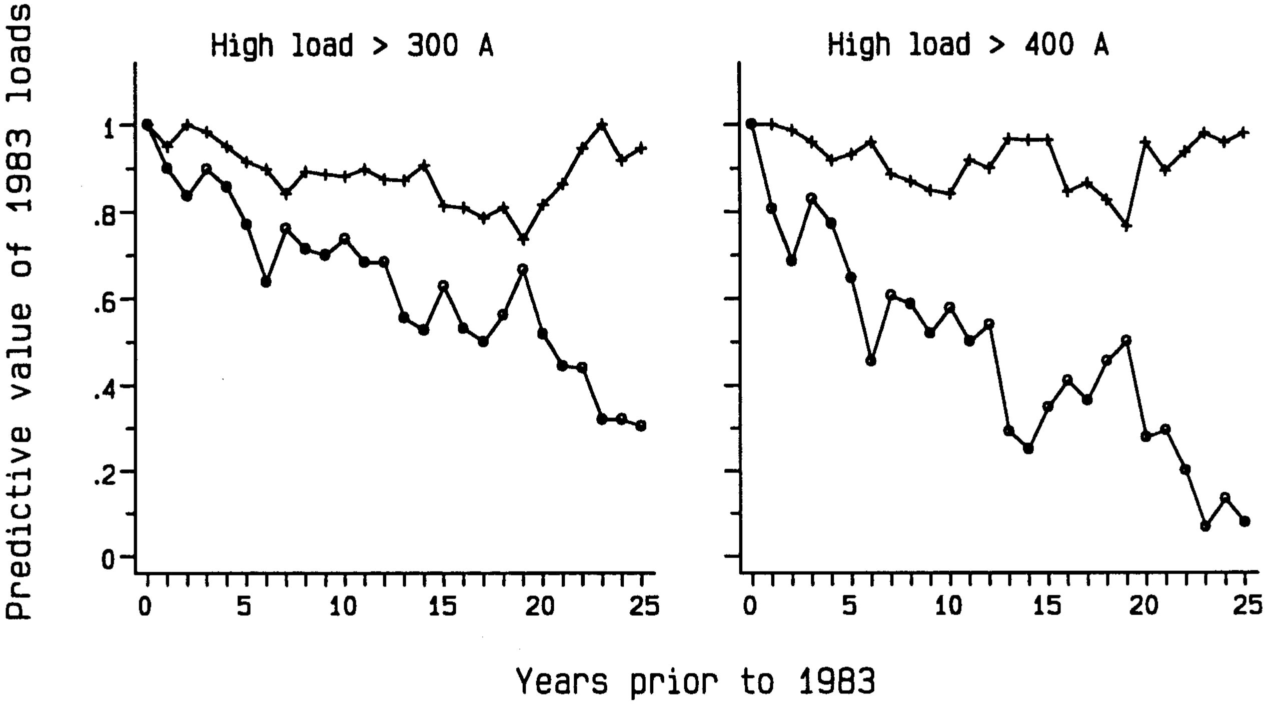

Fig. 8. Positive (o) and negative (+) predictive values associated with the use of 1983 annual average load currents of 112 Swedish transmission lines as predictors for load currents during earlier years.

line load current, observed by removing the daily and weekly rhythms, exhibited some seasonal variation but also included larger components that did not seem related to season (Fig. 4).

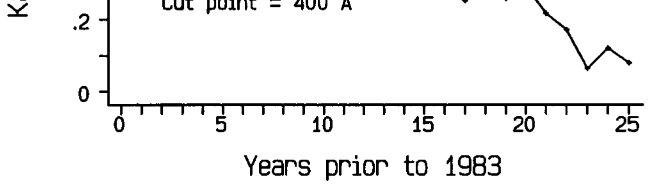

Fig. 9. Values of the kappa statistic characterizing the relation between categorized 1983 annual average load currents of 112 Swedish transmission lines and categorized load currents during earlier years. Data for load currents of 300 A and 400 A are shown.

We then examined annual average load-current data for 112, 220 and 400 kV transmission lines covering the period 1958–1985. These data were used in the Swedish Childhood Leukemia Study to calculate historical magnetic fields for exposure assessment. On the average, transmission-line loadings increased over the period, but at a relatively slow rate of about 3.8 A/y, that is, about 1.3% compounded annually. Annual power-line load currents were placed into high and low categories depending on whether they were greater than or less than or equal to a specific threshold current (300 A or 400 A). Negative predictive values for 1983 load current used as a surrogate for load current during an earlier year were moderately high (>0.73), regardless of the elapsed number of years between the two dates (Fig. 8). However, positive predictive values declined steadily as the period between 1983 and the earlier year increased. At 5 years, the positive predictive value was 0.65 when the threshold current dividing high from low loads was 400 A , which means that only 65% of power lines that had high loads (>400 A) in 1983 had high loads in 1973. At 10, 15, and 20 years, this value decreased to 0.58, 0.35, and 0.28, respectively. Clearly, 1983 load current categorized as described above was not a very good predictor of categorized loads during earlier years, especially for years prior to about 1973. In this context, it is perhaps worth noting that this method of categorization—using the same cut point for historical exposure and a contemporaneous surrogate measure of exposure—is standard for magnetic-field exposure assessment in epidemiological research. Our conclusions are similar to the main conclusions of a recently published study of the temporal behavior of transmission-line load current in Norway [Reitan et al., 1996].

The discussion in the preceding paragraph shows that the use of a fixed cut point to place transmission line load currents into high or low categories does not yield a very good prediction of historical transmission-line load current categorized using the *same* cut point. The lack of concordance between ''historical'' and ''contemporaneous'' categorized load current could stem from two sources: 1) pseudo-random temporal variability; or 2) a systematic increase or decrease in load current over time. This distinction is important because if the latter mechanism is the dominant reason for the lack of concordance between contemporaneous and historical measures of load current, it would still be possible to predict historical categorized load current from a contemporaneous value by using *different* cut points for the two. Indeed, two characteristics of our load data would suggest that this might be the case. First, as we have already noted, average transmission-line loading increased by 1.3%/y. Second, if the major impact of time was a systematic increase in transmission-line loading, 1983 loading classified as ''low'' would always be associated with ''low'' loadings during earlier years, whereas 1983 loadings classified as ''high'' would not necessarily be associated with ''high'' loadings during earlier years. In the language of predictive values, negative predictive values would be near 1 for all years prior to 1983 while positive predictive values would decrease from 1 as the number of years prior to 1983 is increased. This is, in fact, the behavior observed in Figure 8.

However, if load currents changed in a systematic way over time, we would also predict that Pearson correlations between 1983 loading and loading during earlier years would remain high, because the two sets of data would be approximately linearly related. In fact, if the relation between 1983 load current, I_{1983}, and load current, I_y, during the earlier year y was exponential [i.e., $I_y = I_{1983}(1 - d)^{1983-y}$, where d is the fractional change per year], then the Pearson correlation between I_y and I_{1983} would be precisely 1. Figure 7 shows that, in disagreement with this prediction, the correlation between 1983 and earlier year loadings decreases steadily as time duration is increased. (We were concerned that the results of this test would be ambiguous because the loading data available to us had been rounded to the nearest 100 A. However, Monte Carlo simulations indicated that this rounding would have only a small effect on correlation coefficients and could not begin to account for the decreases in correlation shown in Fig. 7.) Consequently, the lack of concordance between categorized historical and contemporaneous load currents is due not only to systematic increases in load current over time but also to other less predictable sources of temporal variability.

CONCLUSIONS

We began this work with the expectation that transmission-line loadings would be relatively stable over both short and long periods. This expectation was not confirmed for the Swedish transmission lines considered in this paper. Over periods as short as weeks, transmission-line loadings changed substantially, in ways that seemed only partly related to season. Over longer periods of time, annual average loadings increased for some lines, decreased for others, and generally exhibited a wide variety of patterns. The value of 1983 annual load current used as a predictor of earlier load current was rather limited, especially for durations in excess of 10 years. Based on these results, we conclude that Swedish transmission-line loadings were sufficiently variable over time to affect significantly magnetic field calculations based on them.

This conclusion offers a possible explanation for the finding of Feychting and Ahlbom (1993) that only calculated historical magnetic fields, and not contemporaneous field values (measured or calculated), were associated with case/control status in the Swedish Childhood Leukemia Study. In this view, the relationship between contemporaneous and historical magnetic fields was sufficiently weakened, because of the weakened relation between contemporaneous and historical transmission-line loadings, to reduce the association between disease and contemporaneous magnetic fields substantially, even though there may be an underlying causal relation between disease and historical magnetic fields.

Because the results obtained here are derived from an analysis of Swedish transmission lines, they cannot be generalized with certainty to other power delivery systems. There are characteristics of the Swedish transmission system (e.g., its dependence, especially prior to the 1980s, on hydroelectric power generated long distances from population centers) not present in many other power systems that may prevent the results of this paper from being generalized. Furthermore, in the United States, most homes are close to overhead distribution rather than overhead transmission lines. It seems likely that the degree of long-term temporal variation of distribution-line loads may equal or even exceed that of the Swedish transmission lines studied here. Unfortunately, this must remain a conjecture until historical data on distribution-line loading can be obtained. Whatever the case, the results presented here do, at the minimum, raise concerns about the use of contemporaneous magnetic field data as a surrogate for historical exposure in case/control studies that involve historical extrapolation much beyond 5 years.

The results of the paper also offer a possible explanation of why historical magnetic fields might be more strongly associated with simple distance (or, more generally, with wire codes) than with contemporaneous magnetic field data (measured or calculated). Equation (1) states that the magnetic fields produced by a given transmission line at two points in time, one historical (B_H) and the other contemporaneous (B_C), can be written, respectively, as $B_H = GI_H/R^2$ and $B_C = GI_C/R^2$. The use of distance alone as a marker of historical exposure is equivalent to using the expression GI_0/R^2 (I_0 a constant), rather than GI_C/R^2, as the surrogate for historical exposure GI_H/R^2. Clearly, if I_C is closely related to I_H, including I_C in the surrogate measure (i.e., shifting from GI_0/R^2 to GI_C/R^2) will yield an improved surrogate for I_H. However, if the relation between I_C and I_H is weak, including I_C in the surrogate measure may increase random variability (and error) and may thus weaken the relation between the surrogate and the true historical exposure.

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