Exposure of Children to Residential Magnetic Fields in Norway: Is Proximity to Power Lines an Adequate Predictor of Exposure?

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The aim of this work was to study the exposure to magnetic fields of children living at different distances from a power line and to evaluate how well theoretical calculations compared with actual exposure. Personal exposure instruments were carried for 24 h by 65 schoolchildren living 28–325 m from a 300 kV transmission line; the current load was 200–700 A. About half of the children attended a school far from the power line, whereas the other half attended a school located about 25 m from the line. Exposure to magnetic fields was analyzed for three categories of location: at home, at school, and at all other places. Time spent in bed was analyzed separately. The results indicated that children who lived close to a power line had a higher magnetic field exposure than other children. The power line was the most important source of exposure when the magnetic field due to the line was greater than about 0.2 µT. Exposure at school influenced the 24 h time-weighted average results considerably in those cases where the distance between home and power line was very different from the distance between school and power line. The calculated magnetic field, based on line configuration, current load, and distance between home and power line, corresponded reasonably well with the measured field. However, the correlation depends on whether home only or 24 h exposure is used in the analysis and on which school the children attended. The calculated magnetic field seems to be a reasonably good predictor of actual exposure and could be used in epidemiological studies, at least in Norway, where the electrical system normally results in less ground current than in most other countries. *Bioelectromagnetics 18:47–57, 1997.*

Key words: transmission line; exposure calculations; home appliances; school exposure; epidemiology; exposure surrogates

INTRODUCTION

Extremely-low-frequency, especially power-frequency, electromagnetic fields have recently been discussed as an agent with a possible impact on public health. The aspect of electric and magnetic fields that might be relevant to human health outcomes is not yet known. Epidemiological studies indicate elevated risks for some forms of cancer among children living close to power lines. In several of these studies, wire codes were used as a surrogate for exposure to magnetic fields; however, there turned out to be no simple relationship between wire code and measured magnetic field [Savitz et al., 1988; Barnes et al., 1989; London et al., 1991]. Other studies were based on measurements or calculations of magnetic fields, but these may have problems also, because magnetic fields from sources other than power lines (e.g., ground currents, home appliances) may contribute considerably to the exposure.

More recently, instruments that provide continuous recording of personal magnetic field exposure have been used in various epidemiological studies [see, e.g., Floderus et al., 1993; Merchant et al., 1994; Skotte, 1994]. The exposure of children has been determined in several studies, either indirectly by measurements at

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the child's bedroom [see, e.g., London et al., 1991] or by letting the child carry the instrument for 24 h [Allen and Mee, 1994; Feychting and Ahlbom, 1993]. In a U.S. study, the exposure to magnetic fields at home and away from home was evaluated for 28 children ages 4 months through 8 years in the Washington, DC, area in 1990; the children wore AMEX-3D m for 24 h [Kaune et al., 1994]. Their residences were classified according to the wire code of Wertheimer and Leeper [1982], so that magnetic field could only be estimated: the geometric mean both at home and away from home was 0.1 μT. The results suggested that the total time-weighted exposure of children can be categorized accurately by studying only their residences [Kaune, 1993].

The contribution of home appliances to residential exposure has been questioned for years. In a theoretical analysis, extremely-low-frequency magnetic fields generated by several household sources were compared with external sources [Delpizzo, 1990]. The contribution to exposure from electric blankets, waterbed heaters, and concrete slab heaters were found to be comparable with that from power lines.

In preparation for an epidemiological study of childhood cancer and power lines in Norway [Tynes and Haldorsen, 1996], it was decided to carry out a study of personal exposure among children. The study was designed to address two questions: Is the exposure to magnetic fields of children living close to power lines in Norway different from that of other children? How well do theoretical calculations of magnetic fields reflect actual exposure?

The study should provide information on the contribution of sources other than power lines to children's time-weighted exposure to magnetic fields. In view of the present uncertainty about relevant exposures, time-weighted average exposure was the primary measure in this study. Both arithmetic and geometric means were calculated and are presented in the tables, whereas the figures present geometric means only.

MATERIALS AND METHODS

The study population comprised 65 schoolchildren ages 7–12 years who were chosen from class lists at two schools in one suburb of Oslo. The parents of these children led us to additional children in the same district. Many types of dwelling were included one-family homes, apartments, semidetached houses, and town houses. The children all lived within 325 m of one particular 300 kV transmission line. The distances between homes and the transmission line were determined from detailed maps and from actual measurements in a few cases. Distances are given as the distance from the central conductor to the nearest corner of the house/apartment in which the child lived. Magnetic fields at night were calculated by adding 0, 5, or 10 m, depending on the situation of the child's bedroom relative to the corner of the house closest to the power line. The difference in height between the power line and the child's bedroom was evaluated for houses/apartments closer than about 50 m to the line.

Nearly all children attended one of two schools: 28 were at a school located about 300 m from the line (*school A*), and 31 were at a school located about 25 m from the power line (*school B*). Three children attended other schools located far from any power line. Three children did not go to school on the day they carried the personal exposure instrument.

Children wore a personal exposure instrument in a leather case attached to a belt at the hip. The display was turned off, and the case was sealed, so that the child could not touch any switches. The children and their parents were instructed to place the instrument near the child's bed at night but not close to an electric clock or other appliance. The children and their parents kept a diary of activities (*activity list*) for the period of registration, and this was used to classify the location of the child as *at home*, *at school*, or *away from home* (school not included). Time spent *in bed* was a subcategory of at home.

The three-dimensional 50 Hz magnetic field was measured with two Positron electromagnetic dosim (Positron Industries Inc., Montreal, Canada) every 5 s over 24 h and stored in the instrument. The results were then transferred to a portable computer. The instruments have a narrow band frequency response (3 dB points at 42 and 60 Hz) and measure the magnetic field simultaneously in three perpendicular directions. The instrument can discriminate between only 16 levels of magnetic field: values < 0.012 μT, values between 0.012 and 0.024 μT, values between 0.024 and 0.048 μT, and so on. Thus, for each level, the magnetic field increases by a factor of two. The maximal level corresponds to fields > 200 μT. This is a very crude scale, imposing several difficulties in the analysis of the data. The dosim were calibrated several times during the study, using field values when the reading changed from one level to another. The instrument responses were reproducible and were stable over time, and the limits of the different fields levels differed $<$10% relative to an absolute scale. In the analysis of the data, the (arithmetic) mean value within each magnetic field level was used to indicate the field at that level.

Because the software that accompanied the instrument was not flexible enough for our work, we wrote new software to extract data from the raw binary files and to perform the analysis. The program makes it possible to analyze separately data for periods when the child was at home, at school, and elsewhere on the basis of the activity list. The data for the time the child was in bed could be analyzed separately from the rest of the data at home.

Because some of the information in the activity lists was not very precise, we plotted all registrations (17 280 data points per 24 h) for each child and compared them with the activity list. For nine subjects, the start time given by the operator did not correspond to the child's clock: The difference (time shift) was usually <10 min, but, for two of the children, the start of the data sampling was shifted by several hours because of irregularities in the personal exposure instrument or the software used to transfer data from the instrument to a PC. Even in these cases, it was easy to identify the correct string of data to be used by reference to the detailed activity list. For the remaining 56 subjects, there were totally 456 points of time for changes in location during the 24 h recordings. In about 12% of these changes, there was an obvious inconsistency of <10 min between the time given in the activity list and the time read from the plots, and the time indicated on the activity list was altered. Similarly, 2.9% of the changes differed by 10–20 min, and 1.5% differed by >20 min. The times on the activity list and the overall data string were not changed unless we were completely convinced that the corrections were indisputable. One data set (not included) was discarded because the activity list and the actual recordings did not correspond in an understandable manner. We strongly suspect that the child did not carry the instrument throughout the 24 h (not at school and perhaps not at all). A questionnaire was used to determine the kind of house the child lived in (detached house, semidetached house, row house, or apartment building), the type of heating (central heating, panel heater, heating cable, heating foil, water bed), and which school the child attended.

Theoretical calculations were performed by a computer program written by Dr. Vistnes. The calculations are based on Biot-Savart's equation applied for all current-carrying wires, using a proper vector summation and three phase system. Correct geometry was used, except for the assumption that the wires were straight and indefinitely long. No induced ground current was taken into account.

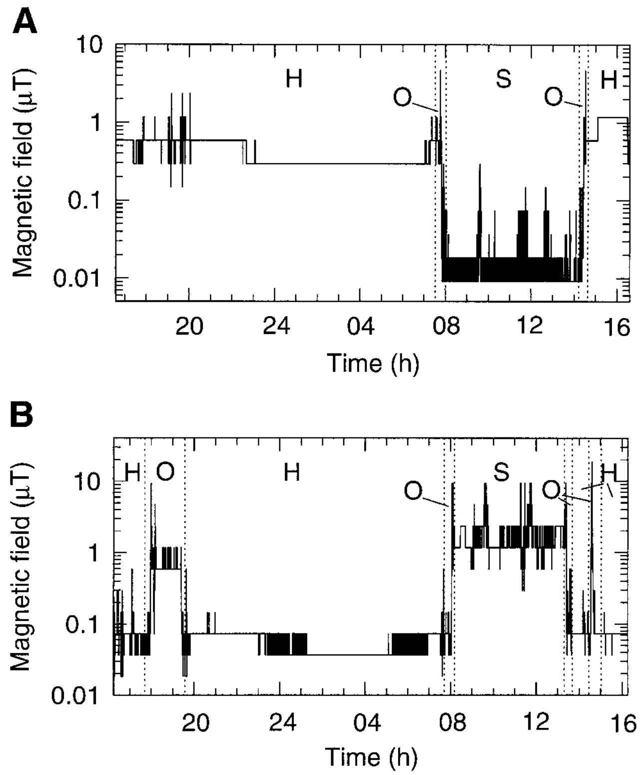

Fig. 1. Examples of magnetic field recordings with the Positron personal exposure instrument. In **A**, the child lived 60 m from the power line and attended a school about 300 m from the line. In **B**, the child lived 175 m from the power line and attended a school only 25 m from the line. H, at home; O, away from home; S, school.

RESULTS

Exposure at home and at school dominated the recordings of magnetic fields. The exposure of a child living 60 m from the line and attending school A and that of a child living 175 m from the power line and attending school B (close to the line) are given in Figure 1. This figure also indicates the activities of the children during the measurement period. For the first child, the only time without considerable exposure to magnetic fields was during school. Most of the exposure of the second child to magnetic fields occurred at school or while playing close to the power line. Most of the children attending school B passed under the power line on their way to and from school or during play in the afternoon. Some children changed activities often during the measurement period, whereas others were more stationary. Note the wide, logarithmic step size for the magnetic field registrations by the Positron instrument.

Power Line Characteristics

The 300 kV transmission line had a horizontal line configuration of 9.2 m between adjacent conductors and a current load of 200–700 A (with one exception). The current load was recorded every hour during the measurement period, which was between March and December, 1991, thus, including periods of both cold and warm weather. The mean current was calcu-

TABLE 1. Time Distribution (In Percent) of Exposure to Different Magnetic Fields of Children Living at Various Distances From a 300-kV Power Line. Analysis is Based on Complete 24-h Exposure for 34 Children Attending Schools Far Away From Power Lines (Three Children Were Not at School During the Measurement Period)

	Time spent at given field level (% of total 24 h)						
Distance (m)	<0.05 μT	0.05–0.20 μT	>0.20–1.54 μT	>1.54 μT	Geometric mean μT	Arithmetic mean μT	No. of subjects N
≤50	15.9	7.7	73.7	2.7	0.36	0.69	3
51–100	28.0	45.8	26.1	0.1	0.09	0.19	7
101–200	39.0	50.2	10.5	0.3	0.065	0.12	15
201–325	83.4	14.8	1.54	0.3	0.025	0.047	9

TABLE 2. Time Distribution (In Percent) of Exposure to Different Magnetic Fields of Children Living at Various Distances From a 300-kV Power Line. Analysis is Based on Complete 24-h Exposure for 31 Children Attending 'School B' Located About 24 m From the Power Line

	Time spent at given field level (% of total 24 h)						
Distance (m)	<0.05 μT	0.05–0.20 μT	>0.20–1.54 μT	>1.54 μT	Geometric mean μT	Arithmetic mean μT	No. of subjects N
≤50	3.0	1.1	92.8	3.1	0.58	0.75	6
51–100	1.5	35.4	57.8	5.3	0.30	0.50	8
101–200	22.7	53.5	15.5	8.3	0.14	0.48	11
201–325	65.4	14.6	16.0	4.1	0.06	0.27	6

lated for the 24 h each subject wore the personal exposure instrument, and a mean value was also calculated for the hours the subject was in bed. The mean of the 24 h means for all 65 recordings was 420 A, and the standard deviation was 126 A. The night mean was 354 A with a standard deviation of 114 A. The mean value for the whole year (365 days of 1991) was 339 A, which included a few weeks with the line under repair and no current. In summary, the load on this particular transmission line was relatively stable, and both seasonal and daily variations were moderate.

Exposure at Different Distances

The data were analyzed with respect to time spent in different magnetic field levels as a function of residential distance from the power line. The data were split in two groups, one for the children that attended the school close to the power line (school B) and one for the other children. Tables 1 and 2 shows the 24 h exposure to four magnetic field intervals and four distances; all of the data were used, and there was no correction for changes in current load (e.g., seasonal) during the study. Children attending a school far from the power line and living closer than 50 m to the power line (Table 1) were exposed to 0.20–1.54 μT for 74% of the full day and night, whereas children at the same school who lived more than 200 m from the line were exposed to <0.05 μT for 83% of the time. For children attending the school near the power line (Table 2), the corresponding numbers were 93 and 65%.

There was a clear correspondence between distance and time spent in all magnetic field levels in Table 1 and 2 except that, in Table 2, there was no apparent correspondence between distance and time spent at fields >1.54 μT. Several of the distributions of magnetic field were far from normal, and the presence of a tail toward the high-field values in some of the distributions led us to present both arithmetic and geometric means. It is unclear which of the two mean values best reflects a possible biological effect.

The reduction in exposure with increasing distance is evident from the mean values, but the degree of reduction depends on which school the children attend. For the schools located far from the power line (Table 1), the geometric mean value is 14 times higher in the ≤50 meter category than for the 201–325 m category; the arithmetic mean is 14 times higher also. For the school located close to the power line (Table 2), the corresponding factors for the geometric and arithmetic values are 10 and 2.8, respectively. There was a difference of a factor of two between the arithmetic and geometric means for the 201–325 m category in Table 1 and of a factor of 4.5 in Table 2.

Table 3 shows the distribution of exposure to

TABLE 3. Time Distribution (In Percent) of Exposure to Different Magnetic Fields of Children Living at Various Distances From a 300-kB Power Line. Analysis Based on Exposure at Home Only for All 65 Children

Distance (m)	Time spent at given field level (% of total 24 h) <0.05 μT	0.05–0.20 μT	>0.20–1.54 μT	>1.54 μT	Geometric mean μT	Arithmetic mean μT	No. of subjects N
≤50	0.0	0.1	97.5	2.4	0.68	0.76	9
51–100	2.2	52.1	45.8	0.0	0.20	0.26	15
101–200	26.2	64.2	9.3	0.3	0.085	0.12	26
201–325	86.7	12.1	1.0	0.1	0.025	0.038	15

magnetic field at home during both the day and the night. Children were exposed to >0.2 μT for 99.9% of the time at home if they lived ≤50 m from the power line, whereas children living >200 m from the line were exposed to <0.05 μT for 86.7% of the time. Note that, in Table 3, the results for all children are included, irrespective of the school they attend.

Six children living 275–325 m from the line spent 95.6% of their time at home in magnetic fields < 0.05 μT (data not shown). The geometric and arithmetic mean values for the latter subgroup were 0.015 and 0.033 μT, respectively. Thus, the exposure at home was 23–45 times higher for children living ≤50 m from the line than for those living 275–325 m away. Children living >50 m from the power line were very seldom exposed to >1.54 μT at home, whereas those living ≤50 m from the line were exposed for 2.4% of the time.

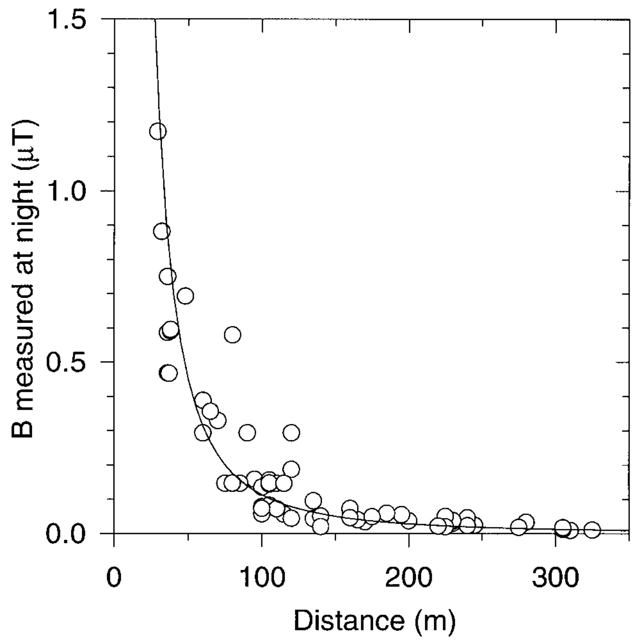

Fig. 2. Geometric means of individual magnetic fields (B) for the 65 children in the study, as a function from the distance to power line, for exposure at night only. No correction is made for differences in load on the power line. The solid line indicates the magnetic field calculated from the mean load during the measurements (night load, 354 A).

Individual Mean Values

The geometric mean exposures of all 65 children to magnetic fields during the night are given in Figure 2. There is a clear relationship between magnetic field during the night and distance from the line, with decreasing field at increasing distance. The data are not corrected for different loads on the power line. The figure also shows the magnetic field from the power line alone (solid line), which was calculated on the basis of the annual mean value of the load. The data broadly follows the theoretical curve.

Calculation vs. Measurements

To understand better the contributions of power lines and other sources to exposure, the calculated fields were compared with measured fields. The results are given in Figures 3–5. In Figures 3 and 4, the set of 24 h data is split according to the school, whereas, in Figure 5, all results for night exposure are given irrespective of school.

A fairly good correlation was seen between measured and calculated exposure, even if the calculations of magnetic fields shown in Figures 3 and 4 were based on the mean current loads during the 24 h of the measurements, regardless of the fact that the children were not at home all the time. This comparison is useful in judging how well actual exposure can be predicted by fields calculated on the basis of the distance between the home and the power line. Both Figures 3 and 4 show that some children living in homes with low exposure have higher observed fields than calculated fields (especially those attending school B), and some children with high exposure at home have smaller observed fields than calculated fields (especially those attending schools located far from the power line).

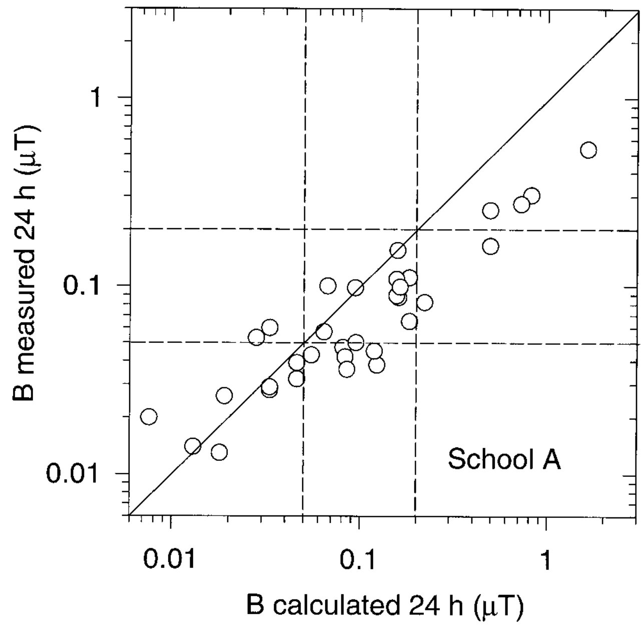

Fig. 3. Measured magnetic field (B) as a function of calculated magnetic field for 24 h exposure of 34 children attending schools located far from a power line or not going to school. The calculated fields are based on the assumption that the child stayed at home all 24 h, which is obviously not true. Solid line indicates a one-to-one correspondence between calculated and measured fields. The horizontal and vertical dashed lines indicate the intervals used for cross tabulation between theoretical and measured magnetic fields (see text and Table 4). The analysis is based on geometric mean time-weighted average (TWA) values.

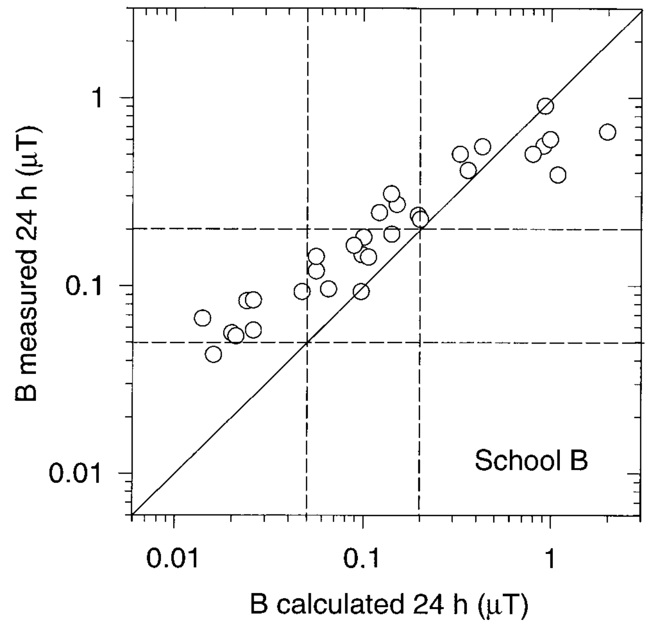

Fig. 4. Measured magnetic field (B) as a function of calculated magnetic field for 24 h exposure of 31 children attending a school located about 25 m from a power line. For other details, see Figure 3.

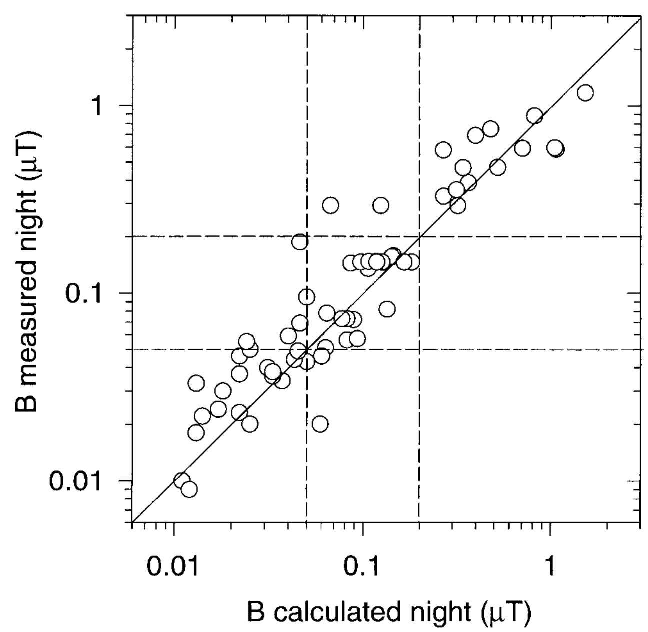

Fig. 5. Measured magnetic field (B) as a function of calculated magnetic field for night exposure only. For other details, see Figure 3.

The results, as we have seen, differ somewhat for children in the two categories of schools. The correlation coefficients between 24 h calculated fields and measured fields (geometric mean) for children attending schools far from the power line were 0.98 (Pearson's correlation coefficient) and 0.86 (Spearman's rank correlation coefficient). For children attending the school located near the power line, the coefficients were 0.81 (Pearson) and 0.96 (Spearman). A fairly high correlation between measured and calculated exposure at night was also seen (data in Fig. 5): 0.88 (Pearson) and 0.93 (Spearman).

Cross tabulation of the results was performed according to the calculated fields and the measured fields. The exposure was classified as *low*, *intermediate*, and *high* according to the limits < 0.05, 0.05–0.20, and >0.20 μT. The classification is indicated by dashed lines in Figures 3–5. Table 4 gives the percent of cases for the different elements in the cross tabulation. For the 24 h exposure of the children attending a school far from the power line (Fig. 3, Table 4, left side), 30% of the observations were off-diagonal; most of these were located below the diagonal (measured field lower than calculated field). For children attending the school close to the power line (Fig. 4, Table 4, right side), 36% of the observations were off-diagonal; all were

TABLE 4. Cross-Tabulation Between Measured and Calculated 24 h Mean Values of Exposure for Children Attending Schools Far From a Power Line (Left) and a School Near the Power Line (Right). The Exposure is Categorized in Three Different Magnetic Fields Intervals, Corresponding to ''Low'', ''Intermediate'' and ''High'' Fields. The Numbers in the Elements of the Two 3 × 3 Matrices Gives the Number of Cases in Percent of the Total in Each Group. Data for One Child is Excluded Since There Was no Current in the Power Line During the Measurements

	Calculated magnetic field for children attending schools far from power line			Calculated magnetic field for children attending school located near power line		
Measured magnetic field	<0.05 μT	0.05–0.2 μT	>0.2 μT	<0.05 μT	0.05–0.2 μT	>0.2 μT
>0.2 μT	0	0	12	0	13	32
0.05–0.2 μT	6	33	6	23	29	0
<0.05 μT	24	18	0	3	0	0

TABLE 5. Distribution of the Measured Magnetic Field Relative to Calculated Field for the Data Given in Figure 3–5. The Numbers in the Table Gives the Number of Cases in Percent of the Total in Each Group, for Various Intervals of the Parameter ''Measured Field Divided by Calculated Field''. The Analysis is Based on Geometric Mean Time Weighted Average Values

Geometric mean TWA value	Percent of all datasets in given category						
Measured magnetic field/ calculated magnetic field	1/5–<1/3	1/3–<1/2	1/2–<1/1.5	1/1.5–1.5	>1.5–2.0	>2.0–3.0	>3.0–5.0
24 h data, school far from power line	6	21	24	39	6	3	0
24 h data, school 25 m from power line	0	6	10	32	16	26	10
Night data only, all children	0	2	6	66	14	9	3

above the diagonal (measured field higher than calculated field). There were no points in the two low/high-field off-diagonal elements.

Cross tabulation is one way to get information about misclassifications. Another possibility is to classify the deviation between measured field and calculated field in a relative manner. This is done in Table 5. For children attending schools far from the power line, 3 of the cases have a measured field more than 2 times the calculated field, and 27% are less than half of the calculated field. For children attending the school located near the power line, the corresponding numbers are 36 and 6%.

To test for systematic errors in the calculations, Figure 5 was prepared and shows the correlation between night values for calculated and measured fields. The corresponding misclassifications are given in the last row of Table 5. In this case (all children included), 12% of the cases have a measured field more than 2 times the calculated field, and 2% have less than half of the calculated field.

Relationship With Other Sources

The correspondence between observed and calculated magnetic fields was good. Several regression analyses were conducted to determine whether some of the other recorded variables were also important. The difference between the observed field and the calculated field and the logarithm of the ratio between the two were used as dependent variables. The independent variables chosen were distance from the line, 24 h power consumption, panel heater, central heating, heating cable in the bathroom, heating cable in the kitchen, type of housing, season of measurement, and school of the child. All except the first two variables were treated as categorical variables. For exposure at night, none of the variables was statistically important, but, for the 24 h measurements, school and distance were significant predictors. Distance gave a positive regression coefficient because of the effect mentioned in the previous paragraph. Type of housing did not seem to have an effect in this type of analysis.

Exposure at School

The geometric and arithmetic mean magnetic fields during the time the children were at school A were 0.020 and 0.036 μT, respectively, and those for children at school B were 0.84 and 1.21 μT, respectively. The mean values for other schools (three children) were similar to those for school A. The difference in exposure between schools A and B was statistically significant.

Exposure Excluding Home and School

When children are away from home (not at home and not at school), they often stay near the home or the school. Thus, a positive correlation was seen between exposure to magnetic fields outside the home and school and the exposure at home or at school. For children attending school A, the geometric and arithmetic mean values for exposure away from home were 0.05 and 0.18 μT, respectively. The corresponding values for children attending school B were 0.16 and 0.75 μT. No difference was seen in the values for exposure at home for the two groups.

Time Spent at Different Locations

During a normal week day, the children spent about 67% of their time at home, of which the majority (41% of 24 h) was spent in bed. They spent only about 13% of their time away from home (and not at school). Time spent at school was 21% of 24 h for children attending school A and 18% for those at school B. The three subjects attending other schools spent 26% of their time at school.

DISCUSSION

Difference in Exposure With Distance From a Power Line

Our results strongly indicate that, at least for children, exposure from power lines might totally overshadow exposure from local sources in the home. The results clearly indicate that children living close to power lines might experience an exposure to magnetic fields different from other children. The definition of *close* depends on the line configuration and the current load. Our data indicate that, if the magnetic field in the home due to the power line is greater than about 0.2 μT, then the exposure of children is truly different from that of children living much farther away. The result is similar, even if a cut-off at 0.05 μT is used, because of the low background in Norwegian homes.

Some variation in exposure was seen, however, among subjects living at comparable distances from the power line. Most of the variation was due to the fact that the children in the study attended two different schools, one located close to the power line and the other located far from the power line. Detailed comparison of the activity lists and the plots of magnetic fields with time for individual children revealed that local sources also contributed to the magnetic fields. One child had greater exposure while playing computer games; one child had extra exposure while cooking; and, for several children, a short peak in the magnetic field was seen when the child approached the television to switch the set on or off. The overall picture, however, was that exposure was rather stable at home and that the children were only seldom exposed to magnetic fields from home appliances.

The systematic trend that calculated exposure was higher than measured field for children living close to a power line, whereas it was the other way around for children residing far from a power line, could be interpreted as being due to a systematic error in the calculations. However, the results in Figure 5, where night data is used only, indicates that the there are no such error in the calculations. Here, the measured field follows the calculated field without any systematic deviations, except perhaps that of a somewhat higher measured field than calculated, probably due to local appliances.

The spread in calculated field compared with measured field in Figure 5 might be explained by local fields from, e.g., local appliances. Part of the spread, however, might be associated with the large bins in the instrument used for this study: A difference by a factor of 2 in magnetic field was needed to shift from one recorded field value to the next higher value. Even if mean values of the many recordings during a night will tend to smear out the difference in the bin levels, it will not do so in all cases. This effect will be most noticeable for the night data, because the magnetic field during the night often is very constant. To a lesser degree, the effect will probably lead to some excess ‘‘noise’’ in the 24 h data as well.

Our data are in qualitative agreement with the conclusions of several studies: Subjects living close to a power line have a different exposure than subjects living far from a line. In a Danish study [Skotte, 1994], adults living close to a power line (according to a set of criteria) experienced a magnetic field of 0.49 μT (arithmetic mean; geometric mean, 0.29 μT) at home. The mean values for residences far from power lines were 0.06 and 0.04 μT for the arithmetic and geometric means, respectively. Thus, Skotte found a roughly sixfold increase in the mean magnetic fields in houses close to a power line compared with those far away. Similarly, in a small South African study (14 adults), the average exposure to magnetic fields of subjects living close to a power line ($\leq$50 m) was 0.29 μT, whereas that of subjects living far from the lines ($>$150 m) was 0.08 μT [Pretorius, 1994]. The results in Tables 1–3 indicate that the difference between homes close to and far from power lines is greater in Norway than in Denmark or South Africa, but this may be due partly to the stricter classifications used in our study.

Our data are also in qualitative agreement with a study from England by Merchant and coworkers [1994], who found that the strongest identified factor influencing exposure at home was the presence or absence of overhead lines at voltages of 132 kV or above within 100 m of the home. However, Merchant found that the type of housing also influenced exposure, whereas we did not find such an effect in our data.

The data given in Tables 1–3 are interesting, because no corrections were made for differences in load on the power line during the different measurements. We evaluated whether there was a tendency towards a lower power line load on days of measurements of children living far from the line, but no such tendency was found.

It is obvious that the results in Tables 1–3, and all results based on distance only, depend on the power line in question. The design of our study, however, allows more general conclusions to be drawn. A comparison of measured magnetic field with theoretical values (Figs. 3–5) indicates that the results are not limited to the particular power line involved in this work. We have tried to formulate our conclusions so that they do not depend heavily on a particular power line.

During the calculation of magnetic fields, it became evident that, under some circumstances, distance was a more problematic parameter than, e.g., current load. For children living ≤50 m from the power line, the calculated magnetic field differed considerably according to whether the child was assumed to sleep in the part of the house closest to or farthest from the line. We made a crude correction for the location of the child's bedroom in the apartment/house, but we had no records about the most usual location for the rest of the time at home, and we had to use the distance to the nearest corner of the house. Also, although the difference in height between the power line and the rooms in which the child spent most of the time is important for children living very close to the line, the heights were difficult to determine in practice.

Our study shows that exposure at school influences the time-weighted average exposure to magnetic field over 24 h. The influence was maximal, because one school was located very close to the power line, and the other school was located far from the power line. In an English study of 51 children logged for 48 h [Allen and Mee, 1994], exposure at school was also found to influence considerably the total exposure.

Theoretically, children may behave differently while carrying the instrument, and our recordings, therefore, may not reflect the everyday situation. Neither the data nor the activity lists, however, indicated that the children or their parents attempted to create an exposure situation during the test that differed from what the child normally experienced.

Magnetic Field Levels Far From the Power Line

The measurements indicate that the power line contributes significant magnetic fields to about 300 m. The reasons for this are, first, that a 300 kV transmission line with a load of several hundreds of amperes results in considerable power frequency magnetic fields, and, second, that the normal magnetic field in Norwegian homes is very low. Children living >275 m from the line spent about 95% of their time in fields <0.05 μT while at home. Although the arithmetic and geometric mean values were 0.033 and 0.015 μT, respectively, they may be higher than the true values, because they are close to the lowest field measurable by the instrument, and all exposure below 0.012 μT was set equal to 0.006 μT.

The low 50 Hz magnetic field in Norwegian homes was also documented in a small study by Hansson Mild et al. [1996]: They found mean values of 0.013 μT for Norway and 0.040 μT for Sweden. Skotte [1994] reported a level of 0.040 μT for Denmark. The difference between Norway, Sweden, and Denmark can be explained by differences in the electrical systems, because ground currents are common in Sweden and Denmark but not in Norway, unless there is some grounding error [see Hansson Mild et al., 1996]. The exposure to magnetic fields of children living far away from power lines, therefore, seems to be lower in Norway than in any countries in which measurements have been conducted. The number of measurements is limited, however, and, in homes with extended use of, e.g., one-conductor heating cables, the field is obviously greater than 0.015 μT, even if the home is located far from any power line.

Time Spent at Different Locations

Our findings with regard to time spent at different locations were similar to those of Kaune and coworkers in the U.S. [Kaune et al., 1994]. Time spent at home represented 67% of 24 h in our study and 71% in the U.S. study, and the time spent in bed (41% in our study) corresponds well with Kaune's finding of 44% of the time in the subject's bedroom. Our finding of roughly 20% of 24 h at school is similar to the U.S. percentage of 19% at school/day care centers. Thus, it is not a surprise that the remaining time spent away from home (and away from school) is also similar (13% in our study, 10% in the U.S. study). The similarities of the numbers in the two countries is remarkable in view of the many societal differences.

Are Calculated Fields Adequate Predictors of Exposure?

Our study shows fairly high correlations between calculated and actual exposure; correlation coefficients varied between 0.81 and 0.98. These findings might be compared with those of a Swedish study, where Feychting and Ahlbom [1993] obtained a reasonably high correlation between calculated contemporary fields and spot measurements (the Spearman correlation coefficient was 0.70). However, a high correlation coefficient does not necessarily mean that there is a 1:1 correspondence; however, a high correlation coefficient does indicate a good possibility that an epidemiological study will reveal a monotonic relationship between exposure and health effects. The possibility of detecting the exact form of the dose-response relationship might depend to greater extent on other circumstances.

Cross tabulations of calculated and measured fields (Figs. 3–5, Table 4) indicate that misclassification between high and low exposure categories is unlikely, but there might be a considerable misclassification for the intermediate exposure category. The most common type of misclassification depends on the school location relative to the power line. For children attending a school far from a power line, real exposure tends to be lower than calculated exposure for residences close to the power line (due to the time spent on school and away from home) but higher than calculated exposure for residences far from the power line.

For small field values, as mentioned above, measured fields tend to be somewhat larger than calculated fields. There are many possible explanations for this finding, including magnetic fields from local appliances, heating foils, heating cables, and currents in the grounding system due to errors in grounding practices. Several of the largest deviations observed were seen for houses with heating foils and also, to some degree, for houses with heating cables. A large deviation was also seen for a child who slept on a water bed. Unfortunately, we did not record in our questionnaire whether the heating cables were of the one- or two-conductor type, which produce very different magnetic fields. We also did not record whether and to what extent the cables were used during measurements, so that a more detailed analysis of the importance of heating cables is not possible, although heating may be important in another context. In a study designed to find sources for exposure to magnetic fields for children living far from power lines, (one-conductor) heating cables might be shown to be an important factor.

CONCLUSIONS

This study demonstrates clearly that children living close to a major transmission line have a greater exposure to magnetic fields than children living farther away. Even if local sources do influence exposure to magnetic fields, the results clearly indicate that the most important parameter for exposure in our material is magnetic fields from power lines. Local sources of magnetic fields do not usually contribute significantly to the exposure of children exposed to elevated fields, e.g., when the magnetic field of the power line exceeds about 0.2 μT. The exposure at school might influence the 24 h mean values significantly. There is a relatively strong correlation between calculated and measured magnetic fields, but the correlation depends on whether the mean values for the night or for 24 h are used and on whether or not the child attends a school located near the power line.

Our study indicates that, at least in Norway, children living close to a high-voltage power line might be divided into different classes of magnetic field exposure based on calculations. However, no particular values of magnetic fields are the obvious choices for classifying exposure, but the limits < 0.05, 0.05–0.20, and > 0.20 μT were appropriate for this work in classifying exposure as low, intermediate, and high.

The results from the cross tabulations (Tables 4, 5) might lead to the conclusion that calculated fields seem to be more than adequate to establish the existence of an association in epidemiological studies, because the misclassification between high and low is unlikely. However, the calculated fields might not give accurate dose-response information, because the intermediate exposure category is rather heavily misclassified.

The analysis in this study was based on various time-weighted averages, assuming that these are important for any biological response. If it becomes evident, for example, that exposure at night is the most important parameter for biological effects, then exposure, e.g., at school will be of lesser interest.

Caution should be used in extrapolating results from one country to another. In many countries, ground and net currents produce spatially persistent fields [Kaune, 1993], whereas, in most of Norway, this is not a common problem because of an electrical system that is different from the systems in most other countries. The background magnetic field in Norway, accordingly, is low, resulting in exposure distributions that are different from the distributions found in many other countries.

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