Electric and magnetic fields at power frequencies

Anthony B. Miller and Lois M. Green

Exposures to electric and magnetic fields are among the most ubiquitous exposures that the Canadian population experiences. Sources of electric and magnetic field exposures may be occupational or residential and include proximity to certain types of electrical equipment, transmission and distribution power lines as well as appliance use. The early studies of children tended toward a consistent association between risks for leukemia and brain cancer and residential proximity to power lines having high wire configuration.

More recent studies—and studies which have attempted to improve upon the measurement of exposure by using calculated fields, point-in-time or personal monitoring—have been inconsistent, with some suggesting increased risk and others not. Occupational exposures have suggested an increase in risk for leukemia, and to a lesser extent brain cancer and Non-Hodgkin lymphoma. However, studies of residential exposures and cancer in adults generally have suggested no effect. Laboratory work has been unable to demonstrate a biological mechanism which might explain the epidemiological findings.

In spite of extensive efforts over the past 20 years and many expert reviews, it has been difficult to reach consensus regarding the carcinogenic effects of electric and magnetic fields. Exposure assessment has proven to be complex, and agreement on the relevant exposure metric has not yet been obtained. There is justification to question whether point-in-time measures in homes are appropriate indices of the relevant etiological exposure, as they fail to account for changes over time, peak exposures or time-varying fields. Nevertheless, it is probably desirable to err on the side of caution in not placing too much weight on the inconsistencies. The IARC has classified EMF as a "possible carcinogen" which refers to the circumstances where there is limited evidence of carcinogenicity in humans and inadequate evidence in experimental animals. The IARC review indicated limited evidence for the carcinogenicity of extremely low-frequency magnetic fields in relation to childhood leukemia at high level exposure in the residential environment (average residential magnetic field strength $>0.4\ \mu T$). Even higher levels of exposure in the occupational environment may increase the risk of leukemia in adults.

Introduction

Exposures to extremely low frequency electric and magnetic fields (ELF EMF) are among the most ubiquitous exposures to non-ionizing radiation that the Canadian population experiences. In 1979, it was first suggested that residential exposure to ELF EMF might lead to increased cancer risk in children.[1] Since then, a number of studies have examined possible relationships between exposure to a range of electric and magnetic field sources and cancer. High voltage transmission lines and distribution network lines, as well as appliance use, are among the field sources considered in these studies. Studies have been conducted on children and adults in the general population and among workers where high exposure to electric and/or magnetic fields seemed likely. Children may also be exposed in schools or daycare centres.

For the general public, residential exposures seem to be the most contributory and are the type most often considered in studies. As such, we will focus on these as the prime source of environmental exposures. However, as occupational exposures are generally higher than residential exposures, consideration of studies of occupational exposures may be helpful.

General considerations relating to exposure assessment

At power frequencies (50 or 60 Hertz), there is no constant quantitative relationship between electric field strength and magnetic flux density, and it is therefore necessary to measure these components separately. Electric field strength is measured in volts per metre (V/m) and depends upon the voltage in the circuit. Electric fields are easily perturbed and thus stable and reliable measures of personal exposures to electric fields are difficult to obtain. The attenuation of electric fields is so dominant that penetration of the body is minimal; however, these fields do induce currents in the body.

Magnetic flux density is a measure of magnetic field strength per unit area and is quantified by units of tesla (T) or gauss. In contrast to electric fields, power frequency magnetic fields easily penetrate the body and, in general, are not easily shielded. In residential settings, however, the electric and magnetic fields vary temporally and spatially, making the measurement of human exposure difficult and complex.

The ability of epidemiological research to assess the relationship between cancer risk and exposure to electric and magnetic fields is dependent upon the quality of the exposure assessment. Further, in case-control studies in the residential environment where cases have been ascertained retrospectively, measurements of electric and magnetic fields are inevitably taken after the diagnosis of the case and the corresponding time period for the controls. If there has been no major change in the electrical service to the home or in the way the subject spends time in the various rooms in the home and in the external environment, measurements of residential exposures may reflect (to a reasonable extent) the exposure of the subject in the time period relevant to the development of the cancer. However, if the subject has moved, measurements in the current residence may bear no resemblance to the relevant exposures.[2] Few case-control studies have satisfactorily addressed these issues.

Attempts have been made in various ways to develop indices of exposure to ELF EMF that are intended to reflect long-term exposure. The extent to which these efforts have been successful is not clear. It would seem that, at best, these indices reflect a correlate of exposure, or a confounder in the strict epidemiological sense. This is particularly true for wire codes, considered in more detail later in this discussion.[3]

In the occupational environment, there are additional complexities. Job titles have been used in many studies to infer exposure. More recently, job exposure matrices have been developed, accompanied by measurements of specified tasks, with the objective of more accurately reflecting actual exposures. However, even with improved estimation of occupational exposure, total exposure of the worker to ELF EMF is not taken into account. In such studies, it is implicitly assumed that the effect of the residential exposures is small and that what is being estimated is the risk from the occupational exposure alone.

Hence, for most studies, there has been an element of misclassification. To the extent that this misclassification is non-differential, elevated risks probably represent an underestimation of the true risk. Thus, in the absence of a systematic bias, if ELF EMF exposures are indeed carcinogenic, it is likely that, as the precision of measurement of ELF EMF increases, the estimated risks from ELF EMF exposure will also increase. However, if the proportion of cancer incidence attributable to ELF EMF is small and the risk only detectable at relatively high levels of exposure, then a study conducted under circumstances where the proportion of the study population exposed to high levels of ELF EMF is low is likely to demonstrate no association, regardless of the precision of ELF EMF measurement.

The earliest studies of ELF EMF exposures and cancer used exposure assessment methods which were indirect. Exposure was estimated either through categorization of the type of electrical wiring serving the residence, or wire codes, or through static measurements (usually of magnetic fields) within rooms most often used by subjects. The availability of personal monitors that could be worn by an individual has considerably facilitated estimates of individual exposure both to magnetic and, in some instances, electric fields. Developmental work for one such device was conducted by Hydro Quebec, Canada. The device was then adapted and became available commercially as the Positron™ monitor, used in the Canada/France study of electrical utility workers[4,5] and in three case-control studies of childhood cancer and/or leukemia.[6-8]

Determination of the most relevant exposure metric has been hampered by the lack of a biological model suggesting how ELF EMFs may operate in the carcinogenic process. It has been suggested by some that ELF EMF may operate as a promoter. For adults, the length of the induction period for cancer may be very long, such that for residential exposures it may be impractical to attempt reliable estimation over many years. The same difficulty applies to occupational exposures, but the task in these situations may be less problematic than for residential if good historical estimates of exposure can be made. For children's cancers, many of these difficulties are less, as the induction period must be relatively short.

The following review considers exposure circumstance (residential or occupational) by subject (children or adults) with attention paid to the way in which ELF EMF measurements were made. Studies are described in chronological order.

Residential studies

Residential exposures and cancer in children

Wertheimer and Leeper[1] reported a statistically significant two- to threefold increase in leukemia mortality in Denver, Colorado among children in residential proximity to wiring of high current configuration. Exposure to magnetic fields was assessed indirectly according to what has come to be known as the "Wertheimer-Leeper wire code". This code refers to a categorization of electrical wiring of power lines close to residences according to the number of conductors and their diameters, location of transformers and service drops, as well as the distance of the conductors from the home. Increased risk of childhood cancer was observed for those children residing in homes with higher current configurations. Factors such as social class, traffic density and type of neighbourhood (urban versus rural), which the authors thought might be related to either the risk of leukemia or magnetic field exposure, were taken into account.

Fulton et al.[9] attempted to replicate the study by Wertheimer and Leeper[1] in Rhode Island with respect to childhood leukemia. No association was found, but there was some indication that the replication of measurement methodology was not close.

Subsequent studies accomplished some refinement of the wire code by including more comprehensive measures of the distance from the power lines or electrical installations and taking into account line loading. Power lines must be within approximately 100 metres for their electric and magnetic field strengths to predominate over those generated in the homes by household wiring and appliances. Unfortunately, these studies did not use identical "sources" of electric and magnetic fields from which distances were measured, making direct comparisons difficult.

In a case-control study of childhood cancers in Sweden, all cancers and cancers of the nervous system were found to be associated with proximity to 200 kV (kilovolt) transmission lines and with measured residential magnetic field measurements greater than 0.3 μT (micro-Tesla).[10] No excess risk was observed for childhood leukemia, but a statistically significant excess of brain cancer was found. ELF EMF exposure was considered for both birth residence and residence at the time of diagnosis. Controls appeared to be more residentially stable than the cases in this study, but it was not possible to assess how this might have biased the results, if at all. Exposures to magnetic fields were assessed according to distance to electrical conductors and from calculations of magnetic fields from the source. Potential confounders were not considered in the analysis of this association.

In a case-control study of incident childhood cancers in Denver, Colorado, Savitz et al.[11] introduced further improvements in exposure assessment of magnetic fields by carrying out point-in-time or spot measurements inside the child's residence, as well as wire coding. Cases were children diagnosed before the age of 15 years, and controls, matched by age and sex, were selected through random-digit dialling. Of the 70 percent of eligible cases who were interviewed (compared to 80 percent of the eligible controls), only 36 percent had measures of magnetic fields, whereas measurements were available for 74 percent of the controls. Wire codes denoting high current configurations were correlated with higher measured magnetic fields within the home, while wire codes associated with higher magnetic fields were more common among case than control homes. Odds ratios for total cancers, leukemia and brain cancer showed an association with wire code but not with the direct measures of magnetic fields inside the home. The authors suggested that this might be due to the imprecise manner by which a current and point-in-time measurement predicts past exposure. They reasoned that wire codes are more stable over time and thus might "better approximate historical field levels". The authors commented that any trends or excesses observed showed a clearer pattern for leukemia than for other childhood cancers.

Myers et al.[12] studied childhood cancers in Yorkshire, England diagnosed between 1970 and 1979. No association between childhood cancer and proximity to overhead power lines for a child's residence at birth or for exposure to magnetic fields, as calculated on the basis of line-network maps and load records, was observed. Few addresses for cases or controls had background levels of calculated magnetic fields exceeding 0.01 μT.

London et al.[13] used three exposure assessment methods to improve upon the measurement of ELF EMF in their case-control study of childhood leukemia carried out in Los Angeles County, California: 24-hour magnetic field measurements in the child's bedroom, spot measurements of electric and magnetic fields, and wiring configuration as defined by Wertheimer and Leeper.[1] A non-significant elevated odds ratio (OR) was observed for the association between 24-hour magnetic field measurements and leukemia (OR 1.69, 95% Confidence Interval [CI]: 0.71-4.00 for exposure in the 90th to 100th percentile [0.268 μT or more]). A statistically significant association (OR 2.15, 95% CI: 1.08-4.28) was observed for leukemia risk and exposure according to the Wertheimer-Leeper[1] very high current configuration relative to the very low current and underground configuration combined. It was only possible to obtain ELF EMF measurements for about half of the eligible cases, and possible biases, such as residential stability and housing characteristics, were not taken into account. Although the association of leukemia risk with wire code was similar to that reported by Savitz et al.,[11] the mean magnetic field measurements associated with wire code in Los Angeles were lower than those observed in Denver. This, together with the unexplained seemingly wide discrepancy between 24-hour and spot measurements in the London et al.[13] study, adds to the question of what wire codes actually mean.

Feychting and Ahlbom[14] in Sweden attempted to improve estimates of historical magnetic field exposures at the time of diagnosis by using power line load data. With this calculated estimate of magnetic field exposure, significant associations with leukemia risk were observed with the highest level (0.3 μT) of exposure (OR 3.8, 95% CI: 1.4-9.3). Elevated odds ratios for leukemia were also found for those living within 50 metres of a power line. However, no associations were observed with contemporary exposures, whether measured or calculated—findings consistent with those of Savitz et al.[11] and London et al.[13] The authors suggested that their calculated historical fields were reasonably good predictors of past exposure and reasoned that the "lack of an association with spot measurements is consistent with the assumption that fields assessed through contemporary, short-term measurements are poor predictors of past exposure".

In Denmark, Olsen et al.[15] reported significant associations between all major types of childhood cancer combined and exposure to magnetic fields of > 0.4μT from high voltage installations.

A pooled analysis of these two studies confirmed the findings of the components, showing an increased risk of childhood leukemia (OR 5.1, 95% CI: 2.1-12.6) in relation to magnetic field levels of > 0.5 μT.[16]

In a Finnish cohort study investigating cancer risk, Verkasalo et al.[17] found no evidence of an increased risk for leukemia or for all cancers in children living close to overhead power lines. An elevated odds ratio for nervous system tumours for boys was observed with magnetic fields > 0.2μT. However, the small numbers and the fact that one boy had three primary tumours of the nervous system necessitates that the results be qualified.

Coghill et al.[18] conducted a small case-control study of childhood leukemia in England (56 cases and 56 controls) in which the cases were solicited largely by advertising and the controls were selected by the parents of the case. Electric and magnetic fields were measured in the child's bedroom. There was no association with magnetic field exposure, but risk estimates for electric field exposure of 20 volts per metre or more were associated with a significantly increased risk of 4.69 (95% CI: 1.17-27.78).

A case-control study of childhood leukemia in Germany was designed to test several etiological hypotheses.[19] An elevated but non-significant association between high-level exposure (> 0.2 μT) and risk of developing leukemia was found, based on 24-hour measurements of magnetic fields in the bedroom of the residence where the child had lived the longest and spot measurements in residences in which the child had been living for more than one year before diagnosis. The increased risk was based on only four leukemia cases and only 1.5 percent of the study population was exposed to magnetic fields > 0.2 μT.[19]

A nested case-control study assessing cancer risk among children and proximity to high voltage power lines in Norway found no association with leukemia or brain cancer but did find an excess risk for "other cancer sites" in relation to residences within 50 metres from these lines. However, small numbers limited the conclusions that could be drawn from the study.[20]

A large case-control study conducted in parts of the mid-western and mid-Atlantic United States evaluated risk of acute lymphoblastic leukemia in relation to several types of measurements.[21] These included wiring configuration and 24-hour measurements of magnetic fields in the child's bedroom, and magnetic field point-in-time measures in three to four other rooms and just outside the front door of the child's residence. The measurements covered 95 percent of the defined reference period for 77 percent of the subjects. Quartiles of exposure to magnetic fields were defined *a priori*. Slightly over 200 cases were eligible for the analyses of summary time-weighted averages of magnetic fields in the home, although the study enrolled substantially more and 45 percent of these subjects were exposed to magnetic field levels of < 0.065 µT. Subdivisions of the upper exposure quartile showed that one level of exposure (0.40-0.49 µT) was associated with a significant increased risk in both the unmatched (OR 3.28, 95% CI: 1.15-9.89) and matched (OR 6.41, 95% CI: 1.30-31.73) analyses. For the highest level of exposure (> 0.5 µT), similar elevations were not observed either for the unmatched (OR 1.41, 95% CI: 0.49-4.09) or the matched (OR 1.01, 95% CI: 0.26-3.99) analyses. The authors concluded there was lack of support for a relationship with measured magnetic field exposures and the risk of leukemia. Linet et al.[21] also found no evidence of association of leukemia with wire code. Random-digit dialing was used for the selection of controls according to the first eight digits of the telephone number. Depending upon how telephone numbers are assigned within the areas studied, it is possible that this matching by neighbourhood, and hence potentially by wire code, constitutes overmatching and reduced the ability to observe a possible association with wire code.

A cohort study carried out in Taiwan in children younger than 15 years of age at diagnosis showed an elevated leukemia risk (standardized incidence ratio (SIR) 2.43, 95% CI: 0.98-5.01) for those living less than 100 metres from high voltage transmission lines. The risk was more pronounced and achieved statistical significance (SIR 4.70, 95% CI: 1.3-12.1) among children aged five to nine years at diagnosis.[22]

Dockerty et al.[6] reported a study of electromagnetic field exposures and childhood cancers in New Zealand. For the leukemia cases and controls, Positron™ monitors were used in a stationary position to estimate the exposure of children to electric and magnetic fields in the child's bedroom and in the daytime room used most often by the child two years prior to diagnosis. For the 40 case-control leukemia pairs that lived in the houses monitored with the dosimeter, the OR for exposure in the child's bedroom of > 0.2 µT was 15.5 (95% CI: 1.1-224) (based on five cases and one control), while that for comparable exposure in the daytime room was 5.2 (95% CI: 0.9-30.8) (based on seven cases and three controls). No association was seen for tertiles of exposure. There was a suggestion of an elevated risk for the highest categories of electric field exposure, but all lower CIs were below 1.0.

Dockerty et al.[23] were prompted to reanalyse their data using a combination of measurements and different cut-points in order to facilitate comparisons with the large UK case-control study of childhood leukemia.[24] Only 40 case-control pairs had measurements which were potentially relevant to the etiological period. The reanalysis of the time-weighted averages of magnetic field measurements in the child's bedroom and living room showed a non-significant association between increased leukemia risk (OR 3.3, 95% CI: 0.5-23.7) and exposures of 0.2 µT or more when adjustment was made for potential confounding variables. Small numbers limited the interpretation of this analysis, as did lack of details pertaining to exposure assessment and differences in the methods used in this and the UK study.

A study conducted in British Columbia, Alberta, Saskatchewan, Manitoba and Montreal, Quebec evaluating childhood leukemia risk used personal monitoring as part of the exposure assessment.[8] In this study involving 399 case-control pairs, exposure assessment included 48-hour personal ELF EMF measurement, wire coding and magnetic field measurements for subjects' residences from conception to diagnosis/reference date, and a 24-hour magnetic field bedroom measurement. Personal exposure to magnetic fields was not related to leukemia risk (OR 0.95, 95% CI: 0.72-1.26 per 0.2 µT incremental rise in exposure). There was no evidence of increased risk from exposure to elevated levels of electric fields. For magnetic fields measured either in the current or previous residences, there were some indications of increased risk for some of the potential associations examined. For example, subjects who lived in the same residence at least two years before the diagnosis date had an OR for exposures above 0.2 µT of 1.64 (95% CI: 0.89-3.00). Further, there was a non-significant elevation of risk for magnetic field exposure measured at the front door of residences in the highest exposure group (90^{th} percentile, OR 1.59, 95% CI: 0.86-2.93). There was no association with wire code (correction issued after publication of report).

The risk of developing childhood leukemia in relation to electric and magnetic field (EMF) exposures was also evaluated in a population-based case-control study of 201 cases and 406 controls carried out in southern Ontario.[7,25] The mean proportion of the period of inquiry covered by all measured residences was 81 percent for cases and 88 percent for controls, respectively. The corresponding percentages relating to the child's current residence were 71 and 77.

Wire codes were generally not a strong predictor of childhood leukemia. For measured residences with the longest occupancy and according to the highest proportion of time spent at residences with high current configuration, there was no association with childhood leukemia risk. However, for children under six years of age, there was a suggestion of an elevated risk for a very high current configuration wire code in the residence they had occupied the longest (OR 2.88, 95% CI: 0.57-14.50).

Time-weighted averages of point-in-time measurements of magnetic fields around the perimeter of residences and inside the home, the child's bedroom and two other most frequently used rooms were associated with some elevations in leukemia risk.[25] There was, however, no evidence of increasing risk with increasing exposure, irrespective of the location at which the measurement was taken. Residences occupied earliest in the etiological period and for some part of the prenatal period with high wire code configurations were associated with a significantly increased risk of leukemia in children diagnosed before the age of 6 years (OR 3.45, 95% CI: 1.14-10.45). Point-in-time measurements of magnetic fields in residences occupied during the first two years of life and during the prenatal period were also associated with significant elevations in leukemia risk for children diagnosed at a younger age (OR 2.50, 95% CI: 1.14-5.49).

For 88 cases and 133 controls, the residence at the time of interview was relevant to the period of inquiry and these subjects wore a personal monitor, Positron™.[7] For electric fields measured by personal monitoring, there was no evidence of an increased risk of childhood leukemia. Indeed, the risk of leukemia decreased with increasing exposure to electric fields. For magnetic field exposures as measured by personal monitoring, there was evidence of significant associations with childhood leukemia. The risk of developing leukemia increased in magnitude and in statistical significance after adjustment for potential confounders (≥0.14 µT, OR 4.5, 95% CI: 1.3-15.9). Leukemia risk was more pronounced for children diagnosed at younger than six years of age and for those with acute lymphoblastic leukemia, with estimates of risk ranging from 3.7 to 5.7.

Magnetic field exposures in schools were also evaluated in the study by Green[26] and were on average much lower than those found in residential environments. Among school-age children (five years and older) there was no evidence that exposures to magnetic fields at school were associated with an increased risk of leukemia.

One of the largest case-control studies of childhood leukemia was reported in 1999.[24] For a component of this study (2226 matched pairs) magnetic field measurements were made in homes occupied by children diagnosed with leukemia and their control 12 months before diagnosis. The time period of inquiry was limited to 12 months preceding diagnosis, based on the assumption that magnetic fields can only act as a promoter. No account was taken of previous residences or lifetime exposure. Twenty-four- or forty-eight-hour magnetic field measurements were taken in the child's bedroom and in the main family room. No overall association between these estimates of magnetic field exposures and the risk of acute lymphoblastic leukemia, all leukemias, cancers of the central nervous system or other malignancies was found. However, more than 90 percent of the subjects were in the referent group, which was defined by exposures of less than 0.1 µT. For exposures of 0.4 µT or more, the risk for acute lymphoblastic and all leukemia was non-significantly elevated (OR 1.68, 95% CI: 0.40-7.10). Thus, notwithstanding the large number of study subjects, few were in the highest level of exposure. The authors acknowledged that the study had low statistical power to examine associations at higher exposure levels and that a question "may still remain about the effect of exposures higher than 0.4 µT".

Two pooled analyses of the risk for childhood leukemia were published in 2000. Ahlbom et al. found an OR of approximately 2 for children with exposures greater than or equal 0.4 µT, and the Greenland pooled analyses found an OR of 1.7 among children with exposures greater than or equal 0.3 µT.[27,28]

Among subsequent studies, the observation that children with Down syndrome have a 20-fold higher risk of leukemia prompted a case-control study of 42 children with both acute leukemia and Down syndrome as cases and 124 healthy children with Down syndrome as controls.[29] The odds ratio for direct measurements of magnetic fields exposures greater than or equal 0.6 µT was 3.7 (95% CI: 1.05–13.1). The authors suggested the possibility of a role for magnetic fields in the etiology of leukemia among this genetically susceptible subgroup of children. In a study conducted in Japan, the odds ratios for children whose bedrooms had magnetic field levels of 0.4 µT or higher compared with the reference category (below 0.1 µT) was 2.6 (95% CI: 0.76-8.6) for acute lymphoblastic leukemia (ALL) plus acute myelocytic leukemia (AML) and 4.7 (1.15-19.0) for ALL only.[30]

In a study in the North of England of parental occupation, an occupational exposure matrix was used to assign individuals to exposure groups. There was an increased risk of leukemia reported among the offspring of men employed in occupations likely to be associated with EMF or radiation exposures (OR 1.31, 95% CI: 1.02-1.69).[31]

Residential exposures and cancer in adults

Compared to children, there are fewer residential studies relating to adults. Wertheimer and Leeper[32] attempted to replicate and improve upon the methodology used in their original study of childhood cancers in an adult population in Denver, Colorado. They found statistically significant associations for all cancer mortality, cancers of the nervous system, uterus and breast and for lymphomas with increased exposure to magnetic fields assessed by wiring configuration. A major weakness of this study related to the fact that those carrying out the exposure assessment were not blind to the case-control status of the subject.

A retrospective population cohort study was undertaken by McDowall et al.[33] in East Anglia, England, examining cancer mortality for all ages in relation to distance from overhead power lines (30 metres) and from electrical installations (50 metres). The only statistically significant finding was an approximately twofold increase in risk of lung cancer for females, with a dose-response relationship evident for distance from electrical installations.

Severson et al.[34] investigated population registry-based incidence of acute non-lymphoblastic leukemia (ANLL) in adults in western Washington State in relation to wire codes comparable to those defined by Wertheimer and Leeper.[1] The codes were assessed for the residence closest to the reference date and the longest residence three to ten years before the reference date. Spot measurements of magnetic fields were also made in several rooms in the home. There was no evidence of significantly increased risk with any magnetic field measurement. High wiring configuration was associated with a decreased risk of ANLL.

Coleman et al.[35] used distance between residence and overhead power lines and electrical installations, as well as a measure of the calculated magnetic field over a three-year period, to evaluate adult leukemia incidence in southeast England. A non-significant elevation in risk of leukemia in relation to residential exposure to ELF EMF from power lines and transformer substations was found. However, the authors cautioned that the study had limited statistical power (less than 80 percent) to detect even a threefold excess in risk in relation to proximity to overhead power lines.

Youngson et al.[36] studied hematological malignancies in northwest England and Yorkshire using controls discharged from hospital. Exposures were assessed according to distance from overhead power lines and calculated magnetic fields based on current load. No statistically significant associations were observed, although excess risk was seen for myeloid leukemia.

A retrospective cohort study design was used to compare observed and expected deaths among residents who had lived five years or more in a section of Maastricht, Holland which had two 150 kV power lines and one transformer substation.[37] Exposure was defined according to distance from power lines or substation; exposed were those living at distances less than 100 metres with associated measured magnetic fields of 0.1-1.1µT; the referent was defined as distances greater than 100 metres with magnetic field exposures of 0.02-0.15 µT. The standardized mortality ratios (SMR) showed no associations between exposure as defined and those cancers with previously reported relationships with ELF EMF.

Feychting and Ahlbom[38] evaluated excess risk of myeloid leukemia in adults in relation to residential magnetic fields, assessed according to distance from power lines. Magnetic fields generated by power lines were calculated and archival information on line current was used to make historical corrections. Excess leukemia risk was observed for cumulative exposure of 2.0 µT-years or more during the 15 years preceding diagnosis, and distance of 50 metres or less from the lines.

A study of residential exposure and adult cancers (leukemia, brain and female breast cancer) in Taiwan[39] showed a statistically significant increased risk of leukemia with measured magnetic fields greater than 0.2 µT (OR 1.4, 95% CI: 1.0-1.9) and with residential proximity (at time of diagnosis) of less than 50 metres to the nearest transmission line (OR 2.0, 95% CI: 1.4-2.9). No evidence of risk was observed for the two other cancers studied.

A study from Finland found no evidence of increased risk of leukemia in adults, although an excess of multiple myeloma in men and colon cancer in women was observed.[40] Exposure was based on calculations of the average annual magnetic fields, similar to that used for the childhood study.[17] Some elevated ORs were observed in the upper two exposure categories in a Norwegian study of 1068 hematological cancers, but the results are based on small numbers and no firm conclusions can be drawn.[41] Analysis of total leukemia using 0.4 µT as the upper residential cut-off point gave an OR of 1.6 (95% CI: 0.6–3.8), nine cases. Analysis of linear trend using exposure in the 10 years before diagnosis in the case showed a borderline statistically significant result for chronic lymphatic leukemia (CLL) and all hematological cancers. In a similar Norwegian study of breast cancer with 1830 cases and 3658 controls, women with residential exposure greater than or equal 0.05 µT had an odds ratio of 1.58 (95% CI: 1.30-1.92) when compared with unexposed women, but there was no association observed for occupation.[42] A population-based case-control study of breast cancer in Seattle, Washington that included 813 women 20–74 years of age also reported no association of residential magnetic field with breast cancer.[43]

Exposure to electrical appliances in the home

Electric and magnetic field exposures associated with household appliances can be high because of the close personal proximity with use. As an example, the magnetic flux density of a hair dryer is 6 to 2000 µT at a distance of three centimetres from the hair dryer, whereas at a distance of 30 centimetres this range is $<$0.01 to 7 µT.[44,45] Because magnetic fields are greatly attenuated with distance, electric blankets, electric razors, hair dryers, and water beds are candidate "appliances" for evaluation of potential risk because of their close proximity to the body during use.[13,34,46,47] Savitz et al.[47] found a non-significant association (OR 1.7) for childhood leukemia risk and a significant risk for brain cancer (OR 2.5) associated with prenatal electric blanket use. A non-significant leukemia risk was found with postnatal exposure to bedside electric clocks. The authors cautioned against over-interpretation of these results in light of the small numbers and non-response rate. In the study by London et al.[13] examining childhood leukemia, significant risk (OR 2.82) at the 95% level was found with the regular (at least once a week) use of electric hair dryers and (OR 1.49) with black and white television use. In the Dockerty et al.[6] study in New Zealand, appliance use exposure by the mother in pregnancy or directly by the child was evaluated for all childhood cancers. There was no increase in risk for many of the appliance exposures. For electric blanket use by the child before diagnosis, adjusted odds ratios were 2.2 (95% CI: 0.7-6.4) for leukemia, 1.6 (95% CI: 0.4-7.1) for central nervous system cancers and 2.4 (95% CI: 1.0-6.1) for other solid cancers. In the study of Green et al.[26] a preliminary analysis of childhood leukemia in southern Ontario in relation to the use of a number of different appliances common to the residential environment was uninformative.

Occupational exposures and cancer

Early reports of associations between cancer risk and electric and magnetic fields were based primarily on proportional mortality studies using job titles as surrogate indices of exposure to electric and magnetic fields. These studies were followed by case-control and cohort studies using similar indirect estimates of exposure to high levels of electrical and magnetic fields. Collectively, these studies suggested that "electrical occupations" were associated with increased risks of leukemia and/or brain cancer.[48-60]

Subsequent occupational studies were still restricted in exposure assessment by the use of job titles to infer exposures to electric and magnetic fields.[61-65] A case-control study of non-CLL leukemia in a primarily retired population of American Telephone and Telegraph workers found non-significant increased risks.[66] There were similar findings in a study of Norwegian workers.[67]

Floderus et al.[68] carried out a population-based case-control study of leukemia incidence and brain cancer in Sweden. Measurements of magnetic fields were derived from a personal monitor worn for a representative day in the work environment, with a focus on those jobs or tasks held the longest during the ten-year period before diagnosis. Adjustments were made for potential confounders such as benzene, ionizing radiation, pesticides, solvents and smoking. A dose-response relationship was observed for all leukemia and for chronic lymphocytic leukemia, with statistical significance attained at the highest exposure levels. There was no association with acute myelogenous leukemia. Elevated risks were also found for brain cancer and statistical significance was attained, but not in the highest exposure level.

Sahl et al.[69] examined leukemia, brain cancer and lymphoma mortality among workers in a US electric power utility in relation to measured magnetic field exposures and also to employment in electrical occupations defined as "exposed" *a priori*. Using both a cohort and case-control approach, no excess risk of any cancer site under study was observed, although the small numbers place limitations on the interpretation and significance of this study.

Theriault et al.[4] studied cancer incidence in electric utility workers from Canada and France using a nested case-control study design. Current workers, selected according to job title, wore Positron™ monitors which measured electric and magnetic fields. Using these measurements and a work history, a job-exposure matrix was created and applied to cases and controls in each of the participating utilities. The investigators also attempted to control for possible occupational confounders. A statistically significant association was observed for acute non-lymphocytic leukemia and specifically for acute myelogenous leukemia. The excess risk was most pronounced in the Ontario Hydro cohort but also was apparent in the Hydro Québec cohort, where all cases of acute myeloid leukemia (N = 6) were confined to the exposed group and, as a result, the reported odds ratio was undefined.

Savitz and Loomis[70] reported on the mortality experience of five US utilities. Personal monitors were worn, but yielded only a time-weighted average exposure to the magnetic field per worker. An association was observed with leukemia for electricians (OR 2.5, 95% CI: 1.08-5.76) having 20 or more years of employment, and a statistically significant excess of brain cancer mortality (OR 2.3, 95% CI: 1.15-4.56) was associated with magnetic field levels of > 4.3 µT-years. The findings relating to brain cancer showed a significant trend of increasing risk with increasing exposure to magnetic fields.

In the study of electric utility workers in Ontario, Miller et al.[5] raised the possibility that electric fields might be more important than magnetic fields with respect to occupational exposures and leukemia risk. An odds ratio for all leukemia of 4.5 (95% CI: 1.01-19.7) was reported for electric field levels > 345 volts per metre (V/m) years. Further, there was evidence of an interaction between electric and magnetic fields (OR 11.3, 95% CI: 1.52-84.3) for electric field exposure > 345 V/m years and magnetic field exposure > 7.1 µT-years, with the electric field component being dominant in the contribution of excess risk. An association between lung cancer and exposure to both electric and magnetic fields also was suggested.

Guenel et al.[71] also reported findings suggesting that exposures to electric fields might be important in the occupational environment. Among French electric utility workers, increased odds ratios for brain tumours were observed which were statistically significant at the highest exposure level (OR 3.08, 95% CI: 1.08-8.74) and for those with employment of 25 years or more. There was no evidence of increased risk of leukemia with electric field exposure.

Kheifets et al.[72] attempted to evaluate leukemia risk and occupational electric field exposure in Los Angeles County, California. No association was found.

Although in the Canada-France study no association between lung cancer and time-weighted averages of magnetic fields was noted,[4] an association was reported between lung cancer and exposure to pulsed electromagnetic fields (PEMF) in the combined Hydro Québec and Electricité de France data.[73]

To date, only one study has considered both occupational and residential exposures to electric and magnetic fields.[74] Modest increases in risk were observed for leukemia and exposure (0.2 µT) in the residential (OR 1.7, 95% CI: 1.1-2.7) and occupational environments (OR 1.3, 95% CI: 0.8-2.2). Exposure to magnetic fields of 0.2µT or more in both the residential and occupational environments was associated with risk of acute myeloid leukemia (OR 3.7, 95% CI: 1.5-9.4). Central nervous system tumours showed no association with magnetic field exposure.

Kheifets et al.[75] conducted a comparative analysis of the recent occupational studies. They concluded that there was evidence of a weak association between magnetic field exposure and risks of leukemia and brain tumours. They were unable to evaluate electric field exposure.

If some aspect of electric or magnetic field exposure unique to the workplace increases cancer risk, then the use of cumulative time-weighted average (TWA) estimates of exposure may dilute the true risk. The evaluation of other indices of magnetic fields has been done explicitly in some studies.[13,66,68] Other work has assessed cancer risk by using cumulative electric and magnetic field exposures, based on the geometric and arithmetic mean field strength. The arithmetic mean is more sensitive to skewed data and is better suited for modelling threshold effects, whereas the geometric mean, which is closely related to the median of the exposure distribution, minimizes the influence of outliers. However, results from further analyses of the Ontario Hydro study population indicated that the use of the arithmetic and geometric means does not adequately characterize the variability of either electric or magnetic field exposures.[76] Therefore, further analyses have evaluated the association between other indices of electric and magnetic fields and cancer in the Ontario Hydro cohort. Both duration of employment and average annual exposure to electric fields were independently associated with an increased risk of leukemia.[77] The analyses supported the hypothesis that exposure above an electric field threshold is the relevant aspect of field strength to predict leukemia risk.

An Australian study with 694 cases and controls investigated the risk of non-Hodgkin lymphoma (NHL) using a job-exposure matrix (JEM) to assess exposure to occupational magnetic fields at the power frequencies of 50/60 Hz.[78] For the total work history, the odds ratio (OR) for workers in the upper quartile of exposure was 1.48 (95% CI: 1.02 to 2.16) compared to the referent (p-value for trend was 0.006), providing weak support for the hypothesis. A similar Australian study of 414 histologically confirmed cases of glioma did not indicate support for a role of ELF EMF.[79] Also, a case-control study in Germany of testicular cancer with 269 incidence cases and standardized face-to-face interviews indicated ELF EMF was not a risk factor for this cancer type.[80]

Two recent studies of occupational exposure and female breast cancer have reported negative findings and one a positive finding. While the residential component of a Norwegian study of female breast cancer observed an association as noted above, there was no association observed for occupation as assessed individually by an expert panel.[42] In addition, the findings of a Swedish study of occupation and breast cancer using 20,400 cases identified from the cancer registry do not support the hypothesis that magnetic fields influence the risk of developing the disease.[81] The exposure was assessed by linkage to a job-exposure matrix based on personal magnetic field measurements. A study in the Montreal region was undertaken with 608 postmenopausal breast cancer cases and 667 controls. Industrial hygienists assigned to each job an average duration of exposure to ELF EMF at four levels of intensity. Adjusted for other risk factors, an OR of 1.13 (95% CI: 0.94-1.35) for lifetime occupational exposure to ELF EMF at medium or high intensities was reported (greater than or equal 0.5 µT) and risks were larger for exposures before age 35.[82]

Experimental studies

Biological plausibility is one of several criteria used to judge causality. To date, it has not been possible to demonstrate a biological mechanism whereby exposure to electric or magnetic fields causes cancer. Notwithstanding the lack of evidence from laboratory research, it needs to be remembered that the carcinogenic potential of some exposures has been suggested initially by epidemiological research, only to be corroborated much later by experimental studies.[83]

Discussion

In spite of extensive efforts over a period of 20 years and many expert reviews,[44,83-87] it has been difficult to reach consensus regarding the carcinogenic effects of electric and magnetic fields. One of the difficulties has been different approaches to the measurement of ELF EMF and different epidemiological methods used to assess the association.[88] While there have been notable improvements in methods relating to case ascertainment and accounting for other factors, exposure assessment has proven to be complex and agreement on the relevant exposure metric has not yet been obtained.

Studies to date have suffered from lack of specificity with respect to exposure. It is by no means certain that all epidemiology studies have measured the right parameters for ELF EMF exposures. While consistency of reported risks by certain metrics of ELF EMF is the most compelling argument suggesting a causal role for ELF EMF, biological plausibility is weak. Laboratory work has failed to demonstrate a biological mechanism which might explain the epidemiological findings. As a result, there have been few clues about the relevant exposure metric, if any, to apply to epidemiological investigations.

The early studies of children tended toward a consistent association between risks for leukemia and brain cancer and both residential proximity to power lines and high wire configuration. More recent studies have tended not to confirm this association. Because of this and the observation that the earlier studies that used point-in-time "measures" of magnetic fields showed either an acutely attenuated risk or no risk, some have concluded that the association should not be regarded as causal. There are, however, several reasons to question whether point-in-time measures in homes are appropriate indices of the relevant etiological exposure, as they fail to account for changes over time, peak exposures or time varying fields.

While several studies have shown measured magnetic fields do increase with higher wire configuration, the disparate associations of these two "measures" observed with leukemia risk have led to the speculation that wire code may be a surrogate for the true etiological agent. Research directed at a better understanding of the correlates with wire code, such as traffic and housing density is underway.[89] Many of these potential correlates are related to socio-economic status. It has been proposed that wire configuration is more stable and, as such, may be superior to point-in-time measurements as an indicator of integrated exposure over time.[88] However, wire codes have been tested in relatively few urban environments, and there is a need to gather more information to determine if the presumed meaning of wire code changes with the geographic location/jurisdiction.

Measures of exposure-as-distance-from-electrical-installations almost certainly suffer from substantial misclassification, especially if it is not possible to take the exposure directly experienced by the subject in the house into account. The Scandinavian studies of children and adults attempted to incorporate historical corrections with distance to better estimate lifetime exposures, and several of these studies support increased risk, especially of childhood leukemia, if the residence is within 50 metres of a power line. Kaune et al.[90] suggested that a significant increase in leukemia risk is seen with exposure calculated from historical line-load data, but not with current measurements. The authors found that the correlation between the current measured value of magnetic field and the calculated magnetic field using historical line-loading data diminished to zero as the historical data extended back more than five years. This argues that studies using contemporary measurements of magnetic fields may not capture the relevant exposure if the etiological period extends back many years.

In addition to the difficulties in interpretation posed by the different methods of ELF EMF exposure assessment, potential selection and information biases may exist in several of the published childhood cancer residential studies, and it is not possible to determine how this might have influenced the results. Some studies have imposed a residency requirement on the controls.[10,11] This has led to the criticism that the controls might be more residentially stable than cases, a situation which in turn might be associated with other lifestyle or socio-economic characteristics that may confound the relationship between leukemia risk and magnetic field exposures.[91] By studying defined areas of Columbus, Ohio, Jones et al.[91] found that "high wire codes were associated with homes in which the residents were mobile and low wire codes were associated with homes occupied by stable residents".

Differential non-participation of controls as function of socio-economic status was proposed by Gurney et al.[92] as a possible explanation of the association between wire codes and childhood cancer. Their study in Washington state found that non-participants were more likely to have lower income, which was in turn found to be associated with very high wire configuration. The studies by Savitz et al.[11] and London et al.[13] have the potential for this non-response bias.

A similar concern might be raised over the method of control selection used in the study by Green et al.[7,25] (telephone-based sampling from lists obtained at one time period). The selection of controls was not concurrent with the cases and bias might have resulted from the controls being more stable than the cases. Cases and controls in the Green et al.[7,25] study did differ significantly with respect to residential mobility, a factor which is potentially related to socio-economic status. There was an inverse relationship between number of residences and family income, with lower income families moving more often. Residential mobility was also an influential variable in all the multivariate models; children who moved more frequently had higher risks of leukemia. Although both the Green et al.[7,25] and McBride et al.[8] studies detected an association between mobility and leukemia risk, the results of the two studies differed; after taking mobility into account, the Green et al. study[7,25] detected a significantly positive association between residential exposures to magnetic fields and leukemia, whereas the McBride et al. study[8] did not.

The paper by Borugian et al. underscores the relevance of socio-economic status as a risk factor for childhood leukemia.[93] A slightly lower relative risk of childhood leukemia was observed in the poorest quintile compared with the richest (RR = 0.87; 95% CI: 0.80–0.95). The lower risk in the poorest quintile was restricted to acute lymphoid leukemia (0.86; 0.78–0.95).

To assess the possibility of bias from the selection of non-concurrent controls in the Green et al.[7,25] study, risk estimates for outside point-in-time measures of magnetic fields were calculated for those diagnosed at less than six years of age by including only controls who had lived in one residence. These risk estimates were attenuated relative to analyses where no mobility restriction was applied to the control population. However, when risk estimates were calculated including only controls that lived in more than one residence, they were higher than those calculated with no mobility restriction applied to the controls. These results suggest that, if it had been possible to include more mobile controls, the risk estimates might have increased. Thus the results from the study may underestimate rather than overestimate the risk of leukemia. Green et al.[7] also examined non-participating cases and controls with respect to wire code of the most current residence and found no differences. Although non-participating subjects were more mobile than participating subjects, there were no differences observed between cases and controls.

The disparate findings in the two Canadian studies[7,8,25] are currently unexplained. There were substantial similarities, but also differences between these two studies. For example, the investigators met regularly with the sponsors' representatives as the studies proceeded and attempts were made to ensure similarity in the data collected. Thus, although the questionnaires were not identical, they were exchanged and attempts were made to ensure that similar data were collected on potential confounders. The ELF EMF measurement protocols were not identical either. Yet in both studies, personal monitoring using the Positron™ monitor was performed for subjects living in a residence relevant to the period of enquiry and measurements were made of magnetic fields in previous residences. Further, the distribution of exposures to electric and magnetic fields seemed similar; in both studies, the 75th percentile for magnetic field exposures was approximately 0.15 µT.

However, there were major differences in the way the data from the personal monitor were used in the analysis. First, a mean of the measurements over a 48-hour period was computed to estimate exposure in relevant current residences in the McBride et al.[8] study. Given that the majority of cases were ascertained prospectively, it is possible that many of them had not yet resumed their normal activity levels after diagnosis and treatment. Further, the mean includes exposures outside home, i.e., at school and in other circumstances, and these may not represent etiological exposures as relevant as those at home. In contrast, in the Green et al.[7] study, with retrospective assessment of cases, sufficient time had occurred for the cases to resume normal activity. Further, the exposures as measured in the current residence, school and other environments were analysed independently. Indeed, the exposures in other environments were not considered, as they were deemed not to represent etiologically relevant exposures. Second, in the McBride et al.[8] study, personal exposures in previous residences were constructed using regression analyses which used wire codes and the available magnetic field exposures in such residences. This process probably involved substantial misclassification; the correlation was relatively low between exposures actually measured in residences using the personal monitor and those estimated. For this reason, this approach was not attempted in the Green et al.[25] study. Rather, an attempt was made to develop integrated estimates of exposure from the actual measurements made in the relevant residences. Third, although the McBride et al.[8] study was closely pair-matched by age, the matching was dissolved for the analysis, and age was controlled using only strata substantially larger than those used for matching. This process was said to have been adopted in order to avoid too much loss of data, but it seems likely to have introduced uncontrolled confounding by age. This was avoided in the Green et al.[7,25] study by preserving the individual matched design in the analyses.

There is a parallel between the largely negative findings of the McBride et al.[8] study and the study of Linet et al.[21] Both were conducted in areas away from very large conurbations and largely in the west of North America, except for the Montreal component of the McBride et al.[8] study. It would be of interest to determine if there is greater similarity between the findings from Montreal and the Green et al.[7,25] study conducted in the greater Toronto region of southern Ontario, than between the findings from western Canada and the United States.

The largely negative study in the UK, based as it is on substantial numbers of case-control pairs, might also be regarded as strong evidence against the hypothesis that exposure to magnetic fields in the home increases the risk of childhood leukemia. However, as pointed out by Repacholi and Ahlbom,[94] the exposures in the UK may be criticized for being restricted to time-weighted averages and, because of the 220 volt service to the homes, are much lower than those in North America. Thus, there were only four cases and three controls exposed to 0.2 µT and above. The power of this study was, therefore, substantially lower than that of either of the Canadian studies. Further, there has to be concern over the exposure estimates used. They were restricted to the year before diagnosis for the cases and to a corresponding period for the controls—a period that was, in fact, not regarded as being relevant to the defined etiological period for cases and controls older than two years in the Green et al.[7,25] or Linet et al.[21] studies. There was also no attempt in the UK study to derive estimates of exposure for earlier time periods or previous residences.

The studies of residential exposures and cancer in adults generally suggest no effect. However, in most studies, measurements have been confined to one residence (current) for which representativeness of lifetime exposure cannot be assumed. While this issue of studying only one residence is also applicable to studies of children,[2] except for the more recent studies, it would seem to be even more important with respect to adults who have many more years for exposure opportunities to electric and magnetic fields and to known or suspected carcinogens both occupationally and residentially.

In a recent review of adult cancers, Li et al.[95] calculated the statistical power of these studies to detect a doubling of risk with “high” levels of residential exposure. That only four studies[14,33,35,36] had power over 80 percent to detect such levels of risk led the authors to conclude that “inadequate statistical power is more of a concern than bias in explaining the inconsistencies across studies”. The studies where no leukemia risk was demonstrated had a very small proportion of the population exposed to magnetic field levels of 0.2 µT or more, however that measurement was derived.

The studies of electric and magnetic field exposures and cancer risk in workers present the generic advantages of studying occupationally exposed groups. The exposures of workers often can be more accurately measured without bias, as a result of records collected and retained for independent purposes and prior to the onset of disease. However, exposures with respect to electric and magnetic fields in the work environment are very different from exposures usually found in residential settings. Occupational exposures are typically higher and reflect wider ranges than those found in homes, and generalization from occupational to residential environments is not appropriate given the current state of knowledge. Moreover, exposures in a residential setting are comparatively uniform, whereas workers may move in and out of high fields throughout their workday or week. It is possible that measuring exposures in the workplace allows for better distinction between exposure ranges and, as a result, high exposures are more accurately characterized and an association detected.

Occupational studies have tended to show an effect with exposure when a distinction was possible by histological type, with acute myelogenous leukemia showing stronger associations, though a few show associations with chronic lymphocytic leukemia. Such types are rare in children, with the dominant type being acute lymphoblastic leukemia. Higher risks have also been observed with cancer incidence than with cancer mortality.

Particularly, but not exclusively, for adults, historical corrections may be important. Most occupational studies have used current exposures applied to current job titles. Recent studies have attempted to apply a correction factor to account for changes over time; however, there is no way by which the validity of the correction can be assessed and, as a result, current measurements are used to estimate exposures as much as 50 years ago.

Delpizzo[96] highlighted the susceptibility to misclassification by the use of job titles as a surrogate of exposure. Miller et al.[5] found that failure to consider work location in addition to job title, and *a priori* selection of job titles according to "presumed" exposure to magnetic fields can attenuate risk estimates.

The recent finding from further analyses of the Ontario Hydro study, that exposure to electric fields over certain thresholds is the greatest predictor of risk of leukemia,[77] supports the need for more extensive work on alternative dose metrics. It is unfortunate that the measuring instrument used in the largest US occupational cohort[70] did not measure electric fields, while the detail obtained on magnetic field exposure does not permit exploration of thresholds. More evidence on the precise circumstances that increase risk in electric utilities cannot therefore be expected from the United States until new studies are mounted.

Studies of exposures in workers are not generalizable to the members of the public, particularly children. Electric field exposures in the occupational environment are several orders of magnitude higher and show far greater variation than those observed in residential settings or settings typically inhabited by children. The risk of adult leukemia associated with electric fields, as reported by Miller et al.,[5] is related to the level of exposure and its duration. However, exposure levels equivalent to those in the occupational environment are not achievable through usual childhood activities.

In spite of the uncertainties described, it is probably desirable to err on the side of caution in not placing too much weight on the inconsistencies. The IARC has classified EMF as a "possible carcinogen" which refers to the circumstances where there is limited evidence of carcinogenicity in humans and inadequate evidence in experimental animals. The IARC review indicated limited evidence for the carcinogenicity of extremely low-frequency magnetic fields in relation to childhood leukemia at high level exposure in the residential environment (average residential magnetic field strength > 0.4 μT).[97] Even higher levels of exposure in the occupational environment may increase the risk of leukemia in adults.

The National Institute of Environmental Health Sciences in the United States concluded that although the overall evidence is weak, EMF cannot be recognized as entirely safe and as such should be regarded as a possible human carcinogen. This conclusion is based on "limited evidence of an increased risk for childhood leukemia with residential exposure and an increased occurrence of chronic lymphoblastic leukemia associated with occupational exposures".[86] The National Radiological Protection Board in the United Kingdom concluded that there is some epidemiologic evidence that prolonged exposure to higher levels of power frequency magnetic fields is associated with a small increased risk of leukemia in children.[98]

Adoption of regulations by governments for ELF EMF exposure from power lines is not widespread. However the California Department of Education (CDE) provides an example of an official body which has established guidance notwithstanding the uncertainty of the scientific evidence. The CDE has made recommendations regarding school site power transmission line setbacks (California Code of Regulations, Title 5, Section 14010©).

The CDE guidance for overhead transmission line easement setbacks as measured from the edge of easement of overhead transmission lines to the usable portions of the school site are:100 feet for 50-133 kV line (interpreted by CDE up to < 200 kV); 150 feet for 220-230 kV line; 350 feet for 500-550 kV line.[99]

This guidance was developed in consultation with international experts on the health effects of electric and magnetic fields (EMF), state agencies such as the Department of Health Services, the Division of the State Architect, and the California Public Utilities Commission, electric utilities, school districts, consultants, and private citizens with an interest in the topic.[99]

The CDE recognizes other hazards need to be considered when locating a school, such as major roads or long distance busing of students. In certain instances, the setback distance can be measured from the transmission line (at ground level) instead of from the edge of easement, and setback distances have been reduced for underground transmission lines.

Summary

1. The current evidence relating to averaged magnetic field exposures greater than 0.4 μT and leukemia in children suggests, but does not prove, a causal relationship.

2. Studies of workers occupationally exposed to high levels of electric and magnetic fields also suggests an association between high level ELF EMF exposure and an increased risk of cancer, specifically acute non-lymphocytic leukemia.

3. There is inadequate evidence that residential exposures to electric or magnetic fields are associated with increased cancer risks for adults.

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