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Socio-Economic Technical Data Reports

2.7 Research on Extremely Low Frequency Electric and Magnetic Fields from Alternating Current Transmission Lines – Summary Evaluation of the Evidence

Health Sciences Practice

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Research on Extremely Low Frequency Electric and Magnetic Fields from Alternating Current Transmission Lines—Summary Evaluation of the Evidence

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Notice

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Contents

Executive Summary

Over the past 35 years, an extensive body of research has developed that addresses extremely low frequency electric and magnetic fields (ELF EMF) and health. As described in Section 1 of this report, ELF EMF is associated with anything that generates, transmits, or uses electricity, so it is a ubiquitous exposure in all technologically advanced societies. As such, questions about whether such exposure could affect our health were raised in the late 1970s, prompted by epidemiologic research that studied the relationship of cancer in children with potential exposure to ELF EMF from nearby power lines.[1] Since that time, researchers from many different scientific disciplines have investigated this question and conducted thousands of epidemiologic and laboratory studies related to the potential effects of ELF EMF, including studies of cancer, reproductive effects, and neurological effects, and many other outcomes.

The current consensus among the numerous national and international scientific agencies that have reviewed this extensive body of research (including the World Health Organization, the International Agency for Research on Cancer, the National Institute of Environmental Health Sciences, the Health Protection Agency of Great Britain [now Public Health England], the Federal-Provincial-Territorial Radiation Protection Committee of Canada, and most recently the European Union's Scientific Committee on Emerging and Newly Identified Health Risks) is that there are no known adverse health consequences of exposure to ELF EMF at the levels generally found in residential and occupational environments, including proximity to electric transmission and distribution facilities. Results from recent scientific research do not provide evidence to alter this conclusion.

Despite the conclusions reached by numerous multidisciplinary scientific panels on behalf of authoritative health, scientific, and government agencies based upon this research, the public frequently expresses concern about ELF EMF, often in the context of proposed new transmission lines. One question that often arises is why scientists continue research if there is strong evidence of no effect. Scientific research and the publication of study results is a constantly evolving process. Scientists that have reviewed research as part of a public health assessments

[1] Wertheimer N and Leeper E. Electrical wiring configuration and childhood cancer. Am J Epidemiol 109:273-284, 1979.

identified above have failed to identify any adverse effects of ELF EMF at levels below guideline limits after extensive testing, which increases the certainty that there are not any risks, or that any possible risk associated with exposure is small. The nature of scientific investigation dictates that it is impossible to prove the absence of an effect, so the possibility that ELF EMF (or any other exposure in our environment) might have some adverse effect can never be completely ruled out. Given the amount and quality of research that has been conducted thus far, however, the opinion of scientific organizations is strong that there is not a cause-and-effect relationship.

A conclusion about any risk associated with ELF EMF can only be reached by an unbiased evaluation of the entire relevant research database using established scientific methods. The scientific research process and the scientific organizations that have carried out evaluations of research on ELF EMF are highlighted in Sections 2 and 3. In Section 4, the current scientific consensus of these organizations and recent key epidemiologic studies related to particular health outcomes, including childhood cancers (leukemia and brain cancer), adult cancers (brain, lymphohematopoietic, and breast), neurodegenerative diseases, and reproductive outcomes, are summarized. Finally, the standards and guidelines that have been established, the precautionary measures that are recommended, and a brief review of some additional research topics are covered in Sections 5, 6, and 7, respectively.

1. Introduction to Electric and Magnetic Fields

In physics, the term field describes the space surrounding a particular object where the properties of that object exert an influence—a temperature field, for example, surrounds warm objects because of the radiating nature of heat. Electric fields and magnetic fields (EMF) surround both man-made and natural sources.[2] Man-made EMF surrounds objects that generate, transmit, or use electricity such as power stations, transmission lines, distribution lines, the wiring in our homes and offices, and the electric tools and appliances and myriad of electronic devices used in everyday life. Electricity in these sources changes direction and intensity 60 times, or cycles, per second—a frequency of 60 Hertz (Hz)—and, therefore, it is referred to as alternating current (AC) power. The 60 Hz[3] EMF associated with electricity is part of the extremely low frequency (ELF) range of the electromagnetic spectrum. Research on ELF EMF has focused primarily on AC power.[4] Fields generated at these extremely low frequencies (i.e., 30 – 300 Hz) differ significantly from the natural static fields (0 Hz) of the earth and fields at higher frequencies characteristic of radio and television signals, microwave ovens, cellular phones, and radar, which can have frequencies up to billions of Hz.

Electric fields are the result of voltages applied to electrical conductors and equipment. The electric field is expressed in measurement units of volts per meter (V/m) or kilovolts per meter (kV/m), where 1 kV/m is equal to 1,000 V/m. Most objects including fences, shrubbery, and buildings easily block electric fields. Therefore, certain appliances within homes and the workplace are the major sources of electric fields indoors, while power lines are the major sources of electric fields outdoors (Figure 1, lower panel).

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[2] Electric fields from natural sources occur, for example, in the earth's atmosphere, which are most commonly experienced during thunderstorms. The earth's geomagnetic field, although it differs in frequency from the 60 Hz magnetic fields generated by AC electricity because it is static field (with a frequency of 0 Hz) , is the dominant form of naturally occurring magnetic fields. The intensity of the geomagnetic field varies with latitude; the lowest values (~ 300 mG) are measured near the equator and higher values (up to ~700 mG) are measured near the north and south poles.

[3] In North America 60-Hz electricity is used, while some other parts of the world, including Europe, 50-Hz electricity is used. Most of the ELF EMF research discussed in this report is thus related to 50 or 60 Hz EMF.

[4] Throughout the world, AC transmission is a more common means of power transmission than direct current transmission. The latter is used primarily for transmission of power across very long distances, with notable examples being Manitoba Hydro's Bipole I and II transmission lines that have been operating since 1972 and 1985, respectively, and the Bipole III transmission line that is under construction and expected to begin operation in 2018.

Magnetic fields are produced by the flow of electric currents. Unlike electric fields, most materials do not readily block magnetic fields. The strength of magnetic fields is commonly expressed as magnetic flux density in units of gauss (G) or milligauss (mG), where 1 G is equal to 1,000 mG.[5] The strongest sources of AC magnetic fields that we encounter indoors are electrical appliances (Figure 1, upper panel).

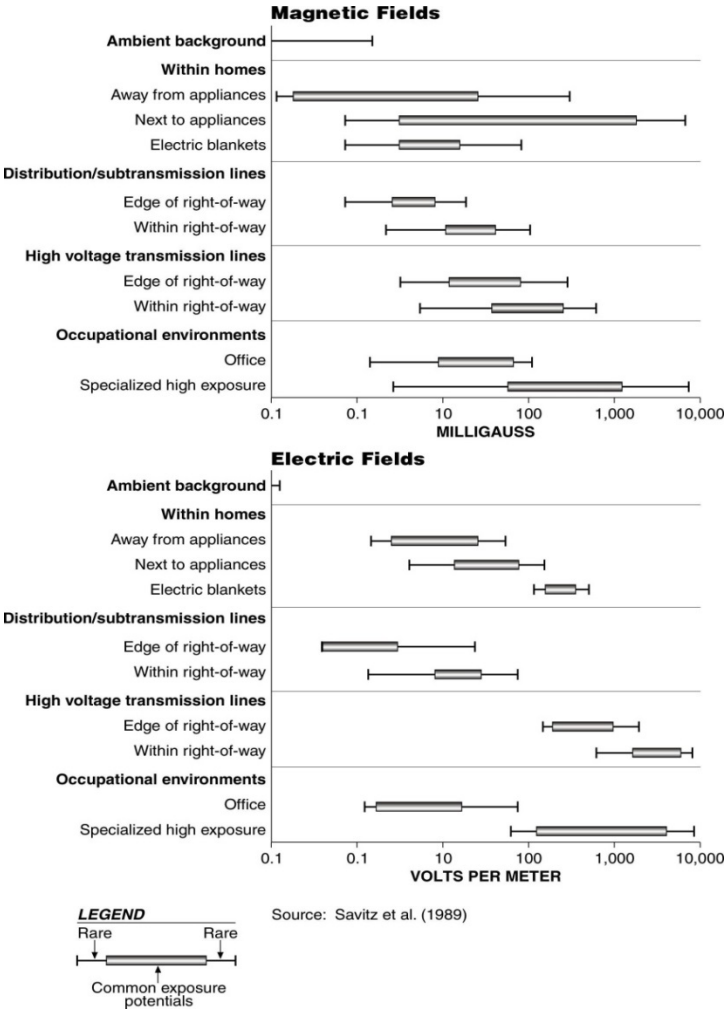


Figure 1. Typical exposure potentials to electric and magnetic fields in common environments.

The level of EMF produced by these sources depends on their structure, location, and various operating characteristics; the magnetic-field level produced by a particular power line, for

[5] Scientists more commonly refer to magnetic flux density at lower levels in units of microtesla (μT). Magnetic flux density in milligauss units can be converted to μT by dividing by 10, i.e., 1 mG = 0.1 μT.

example, depends on the configuration of its conductors, their height from the ground, and the amount of current running through the line, among other factors.

The strength of both electric fields and magnetic fields decreases with distance from the source. Thus, personal exposure to EMF from a particular object depends largely on a person's distance from that object. While appliances tend to produce the highest levels of magnetic fields in our home and work environments, the magnetic fields from appliances drop off more quickly with distance than other EMF sources.[6]

Every individual has a typical background EMF exposure level that is defined by the environments where they spend time, the sources encountered in those locations, and the duration of exposure to these sources. If any of these variables change, the person's average background exposure may be altered. Occupation as a welder or railway worker, for example, would elevate a person's average background EMF exposure for the duration of that employment; or, if a person lived in a home with faulty wiring, his or her average EMF exposure may be elevated during that period. Background levels of magnetic fields (estimated from an average of measurements taken throughout a typical home away from appliances) range from 1-2 mG, while background levels of electric fields range from 0.01-0.02 kV/m; however, in proximity to appliances, magnetic-field levels can be hundreds of times higher and electric field levels tens of times higher, as illustrated in Figure 1 (Savitz et al., 1989; WHO, 2007). The ubiquitous nature of EMF and variability in average background exposure levels make it difficult to quantify levels of exposure for research studies. As a result, a major limitation of health studies of EMF is the methods used for estimating exposure.

Measurement data on Canadian children shows that the average daily magnetic-field exposure is approximately 1 mG (Armstrong et al., 2001). A systematic survey conducted in the United States also indicates that the average magnetic-field exposure in the general population is similar (Zaffanella, 1998). Figure 2 below displays data from measurements taken by a gaussmeter worn by a person for a 48-hour period while conducting ordinary activities at home, at work, and

[6] Fields near appliances vary over a wide range, from a fraction of 1 mG to 1,000 mG or more. Gauger (1985) reported the maximum AC magnetic field at 3 centimeters from a sampling of appliances as 20,000 mG (can opener), 2,00 mG (hair dryer), 30 mG (electric oven), and 7 mG (refrigerator).

in between (i.e., driving and riding the train). These measurements illustrate the continuous but varying levels of magnetic fields that most people encounter each day. Even though high levels of exposure were common and the highest level reached 168 mG, such high exposures were brief. Average exposure over these two days was just a fraction over 1 mG.

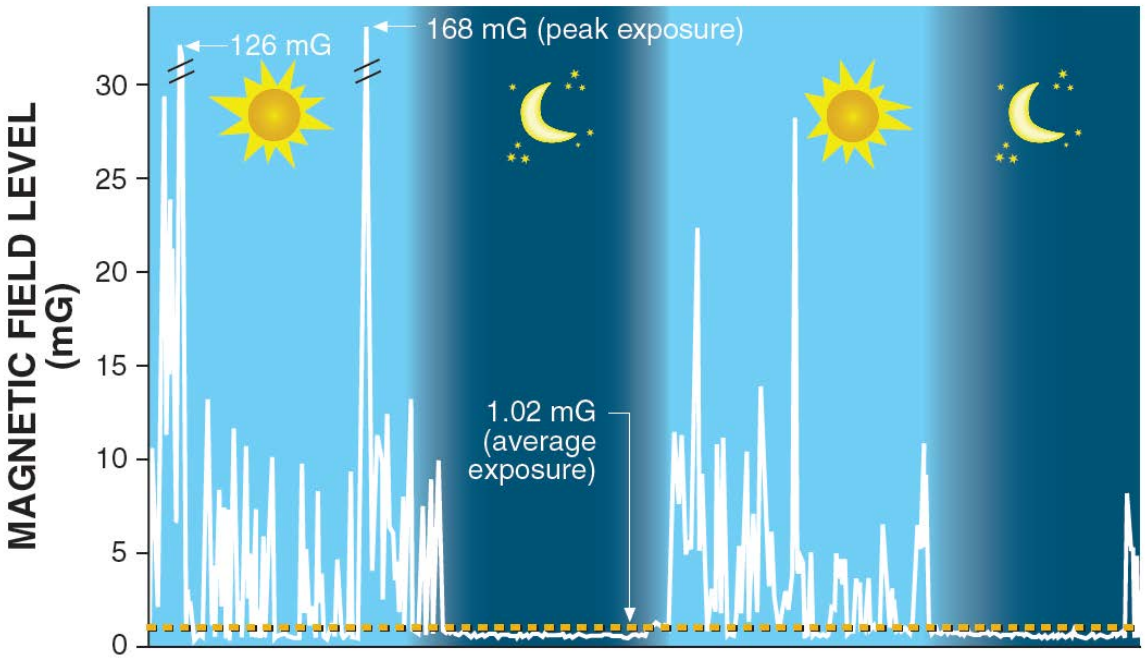


Figure 2. Magnetic field exposure over the course of a 48-hour period.

Source: Exponent (2007)

2. Scientific Research and Review Process

Scientific inquiry is not simply a collection of facts—it is a systematic and unbiased reasoning process used to arrive at accurate and balanced conclusions. The scientific process must, therefore, be conducted in a manner to ensure that conclusions are supported by the research. Many misconceptions in human reasoning occur, for example, when casual observations are made about a particular experience (for example, if a person develops a headache after eating a particular food, he or she may ascribe the headache to the food). Proximity of events or conditions, however, does not guarantee a causal relationship. The same error can occur when conclusions are based on the results of single studies; therefore, scientists use systematic methods to evaluate observations and assess the potential impact of a specific agent on human health.

The scientific process involves looking at *all* the relevant evidence on a particular issue in a systematic and thorough manner, an evaluation that is often referred to as a weight-of-evidence review. This process is designed to ensure that more weight is given to studies of better quality and that studies with a given result are not selected from the available evidence to advocate or suppress a preconceived hypothesis. Conclusions about health risks cannot be drawn from single studies because every study has limitations in one way or another. A weight-of-evidence review is based on a comprehensive assessment of the three main types of scientific research (Figure 3): epidemiologic studies of humans; experimental studies in animals (*in vivo*); and experimental studies in isolated cells and tissues (*in vitro*).

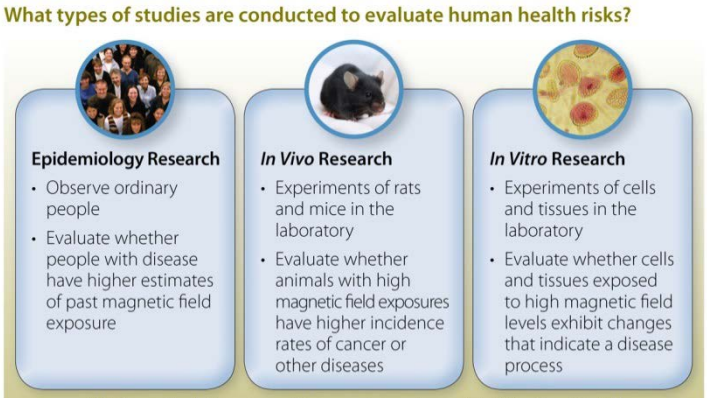


Figure 3. Study types included in a weight-of-evidence review.

The data from all three study types should be considered in evaluating health risks.

A weight-of-evidence review first evaluates individual studies in terms of their strengths and weaknesses and then evaluates all of the studies together, taking the appropriate pieces of evidence from each study to form a conclusion. In this process, the information provided by epidemiologic and *in vivo* studies is complementary. Epidemiologic studies are limited by the lack of control they have over their study participants, but provide information directly relevant to the species of interest; the results from *in vivo* studies, while often more accurate because of the experimental nature of the study, need to be extrapolated to what would be expected in humans. Thus, the overall patterns of results from epidemiologic **and** *in vivo* studies are considered because epidemiologic studies address the limitations of *in vivo* studies and vice versa.[7]

Each study contributes a different type and weight of evidence due to the inherent qualities of its study design, the methods used in collecting and analyzing the data, and any biases that may have arisen during the course of the study. A high-quality epidemiologic study, for example, would consist of a large cohort of a highly-exposed population with follow-up of all its study participants over a long period of time with detailed measurements of exposure for each study participant during the relevant periods of exposure. This study design is expensive and time-

[7] The findings of *in vitro* studies are used by health and regulatory agencies to help them interpret the results of *in vivo* studies, but *in vitro* studies may not be representative of the response to the agent of interest. These agencies, therefore, do not directly rely on *in vitro* studies to make policy decisions.

consuming; thus, other study types (e.g., the case-control design) and dosimetric methods (e.g., job-exposure matrices) are used with a full understanding of their limitations.

The main result of an epidemiologic study is an estimated measure of statistical association between the exposure and disease of interest. When evaluating any study, it is important to consider that its results do not necessarily represent the real relationship between an exposure and a disease; rather, the results represent some estimation of the relationship in a single population, which is limited by the study's methods. In the case of epidemiologic studies, these limitations, among others, may include the unpredictable behavior and many unmeasured characteristics of the study's participants that may also influence their participation in the study or the risk of disease under consideration, and inaccuracies in measurement or estimation of the exposure and the health outcome of interest. In fact, much of epidemiologic analysis involves the interpretation of how outside factors could have affected the study's statistical findings.

Statistical associations in cohort studies are summarized by a computed relative risk, which is a ratio of the risk of the disease in the exposed group to the ratio of the risk in the unexposed group. A value greater than 1.0 indicates a positive association and a possible risk associated with the exposure. Case-control studies estimate relative risks with an odds ratio, which is a ratio of the odds of exposure among persons with a disease (i.e., cases) to the odds of exposure among a similar population without the disease (i.e., controls).

Three factors are always considered when evaluating the weight assigned to any statistical association:

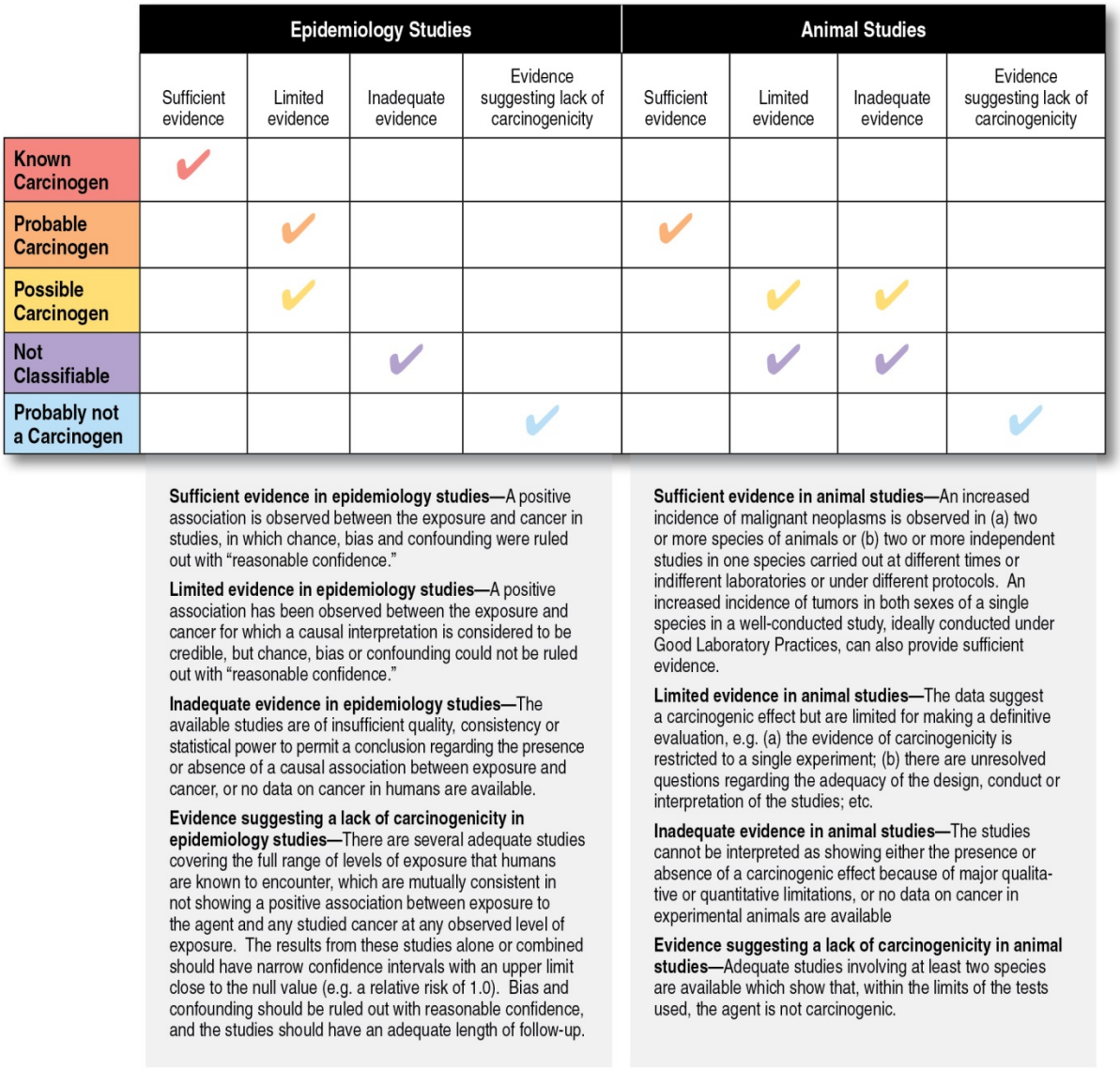
1. ***Chance***. A statistical association may simply be due to a chance occurrence. Statistical tests are performed to evaluate whether chance is a likely explanation.

2. ***Bias.*** Bias is any systematic error in the design, implementation, or analysis of a study that results in a mistaken estimate of an exposure's effect on the risk of a disease. Bias can occur in a study from many sources, including inappropriate selection of study subjects, errors in exposure measurements, and use of inappropriate comparison groups, for example, if a study compares disease rates of exposed and unexposed groups comprised of persons in different age groups.

3. ***Confounding.*** A confounder is a characteristic or exposure that is related to both the disease under study and the exposure of interest such that one cannot be sure what causes the observed association—the confounder or the exposure of interest. With regard to epidemiologic studies of magnetic fields from distribution lines and childhood cancer, some scientists have investigated, for example, whether the association is confounded by exposures to emissions from vehicles on adjacent roadways.

Scientific diligence and care must be taken in the design and analysis of studies to evaluate the role of chance and minimize bias and confounding so these factors do not distort the study's findings.

Scientific panels often classify epidemiologic evidence from all available studies overall as providing sufficient, limited, inadequate evidence in support of carcinogenicity (i.e., the ability of an agent to cause cancer), or evidence suggesting a lack of carcinogenicity, using the standardized classification process established by the International Agency for Research on Cancer (IARC). For the evidence to be considered sufficient, the role of chance, bias, and confounding on the observed association must be ruled out with "reasonable confidence." If the role these factors may play in the observed statistical association cannot be ruled out with reasonable confidence, then the data is classified as providing limited evidence. Inadequate evidence describes a data set that lacks quality, consistency, or power for conclusions regarding causality to be drawn. This classification system is used for both epidemiologic studies and *in vivo* studies and is used to provide summary descriptions of an exposure's potential to cause cancer—known carcinogens, probable carcinogens, possible carcinogens, not classifiable, and probably not a carcinogen (as illustrated in Figure 4).



	Epidemiology Studies				Animal Studies			
	Sufficient evidence	Limited evidence	Inadequate evidence	Evidence suggesting lack of carcinogenicity	Sufficient evidence	Limited evidence	Inadequate evidence	Evidence suggesting lack of carcinogenicity
Known Carcinogen	✔							
Probable Carcinogen		✔			✔			
Possible Carcinogen		✔				✔	✔	
Not Classifiable			✔			✔	✔	
Probably not a Carcinogen				✔				✔

Sufficient evidence in epidemiology studies—A positive association is observed between the exposure and cancer in studies, in which chance, bias and confounding were ruled out with "reasonable confidence."

Limited evidence in epidemiology studies—A positive association has been observed between the exposure and cancer for which a causal interpretation is considered to be credible, but chance, bias or confounding could not be ruled out with "reasonable confidence."

Inadequate evidence in epidemiology studies—The available studies are of insufficient quality, consistency or statistical power to permit a conclusion regarding the presence or absence of a causal association between exposure and cancer, or no data on cancer in humans are available.

Evidence suggesting a lack of carcinogenicity in epidemiology studies—There are several adequate studies covering the full range of levels of exposure that humans are known to encounter, which are mutually consistent in not showing a positive association between exposure to the agent and any studied cancer at any observed level of exposure. The results from these studies alone or combined should have narrow confidence intervals with an upper limit close to the null value (e.g. a relative risk of 1.0). Bias and confounding should be ruled out with reasonable confidence, and the studies should have an adequate length of follow-up.

Sufficient evidence in animal studies—An increased incidence of malignant neoplasms is observed in (a) two or more species of animals or (b) two or more independent studies in one species carried out at different times or indifferent laboratories or under different protocols. An increased incidence of tumors in both sexes of a single species in a well-conducted study, ideally conducted under Good Laboratory Practices, can also provide sufficient evidence.

Limited evidence in animal studies—The data suggest a carcinogenic effect but are limited for making a definitive evaluation, e.g. (a) the evidence of carcinogenicity is restricted to a single experiment; (b) there are unresolved questions regarding the adequacy of the design, conduct or interpretation of the studies; etc.

Inadequate evidence in animal studies—The studies cannot be interpreted as showing either the presence or absence of a carcinogenic effect because of major qualitative or quantitative limitations, or no data on cancer in experimental animals are available

Evidence suggesting a lack of carcinogenicity in animal studies—Adequate studies involving at least two species are available which show that, within the limits of the tests used, the agent is not carcinogenic.

Figure 4. IARC method for classifying exposures according to carcinogenicity

3. Scientific Reviews of ELF EMF Health Research

Multidisciplinary scientific panels of both international and national scientific and governmental agencies regularly conduct weight-of-evidence reviews about possible health risks—it is these evaluations and the conclusions stemming from them that guide research priorities and help set standards and guidelines to reduce potential risks that may be associated with exposures. Numerous weight-of-evidence reviews of the research literature on exposure to ELF EMF and possible adverse health effects have been conducted by international and national scientific and governmental agencies. The major agencies that have reviewed this topic are listed below in Table 1, with their most recent weigh-of-evidence review indicated.

Table 1. Weight-of-evidence and other major reviews, 1998 - 2015

Year	Agency	Publication
1998	National Institute for Environmental Health Sciences	Assessment of Health Effects from Exposure to Power-line Frequency Electric and Magnetic Fields: Working Group Report
2002	International Agency for Research on Cancer	IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. Volume 80: Static and Extremely Low-Frequency (ELF) Electric and Magnetic Fields
2004	National Radiological Protection Board of Great Britain[8]	Review of the Scientific Evidence for Limiting Exposure to Electromagnetic Fields (0-300 GHz), Volume 15, No. 3
2005	Federal-Provincial-Territorial Radiation Protection Committee	Health Effects and Exposure Guidelines Related to Extremely Low Frequency Electric and Magnetic Fields—An Overview
2007	World Health Organization	Environmental Health Criteria 238: Extremely Low Frequency (ELF) Fields
2010	International Commission on Non-Ionizing Radiation Protection	Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz)
2013	Swedish Radiation Safety Authority	Research 2013:19 - Eighth report from SSM:s Scientific Council on Electromagnetic Fields
2015	Scientific Committee on Emerging and Newly Identified Health Risks of the European Union	Health Effects of Exposure to EMF

None of these agencies has concluded that exposure to ELF EMF is a demonstrated cause of any long-term adverse health effect. Section 4 describes the current scientific evidence with regard to specific health outcomes. The "limited" evidence in support of a causal relationship is weak

[8] The agency was renamed the Health Protection Agency in 2004 and then Public Health England in 2013.

because it is primarily based on a statistical association reported in *some* epidemiologic studies between higher estimated average magnetic-field exposure and childhood leukemia. No consistent or convincing associations were observed overall for other health outcomes in epidemiologic studies. Overall, the *in vivo* studies did not report an increase in cancer among animals exposed to high levels of electric or magnetic fields, and *in vitro* studies have not confirmed a mechanism that would explain how electric or magnetic fields could initiate disease.

Most notably, a weak statistical association was reported between childhood leukemia and estimates of long-term exposure to high average magnetic-field levels (3-4 mG). The overall body of research, however, does not indicate that this association, or any other, is causal in nature. Weaknesses in the epidemiologic studies of childhood leukemia limit the significance of their findings; specifically, scientists have not been able to rule out the possibility that confounding or bias contributes to the statistical association between magnetic fields and childhood leukemia reported in these studies. Furthermore, findings from *in vivo* and *in vitro* studies do not support a causal relationship.

The only studies that can be said to confirm a relationship between electric fields or magnetic fields and an adverse biological or health effect are those in which very high levels of exposure to these fields produce currents and fields in the body, which can result in a shock-like effect. The levels at which these short-term effects occur are very high and are not encountered in typical environments accessible to the public, including areas near electric transmission and distribution facilities, nor can these levels be reached even in high exposure occupational environments. Several organizations have recommended exposure guidelines to protect the public and workers against these known short-term effects. These guidelines are summarized in Section 5.

The conclusions of the most extensive of these scientific reviews—the World Health Organization's (WHO) review—which was published in 2007, are summarized in Appendix 1. No adverse health effects were identified in relation to ELF EMF exposure. The WHO currently includes the following statement on its website:

Based on a recent in-depth review of the scientific literature, the WHO concluded that current evidence does not confirm the existence of any health consequences from exposure to low level

electromagnetic fields.[9]The Federal-Provincial-Territorial Radiation Protection Committee (FPTRPC) of Canada released a statement in November 2008 that concluded the following with respect to EMF and health:

> *In summary, it is the opinion of the Federal-Provincial-Territorial Radiation Protection Committee that there is insufficient scientific evidence showing exposure to EMFs from power lines can cause adverse health effects such as cancer.*

This conclusion is consistent with statements in Health Canada's Fact Sheet on EMF, "*It's Your Health*" (see Appendix 2) and by Health Canada currently published on the website of the Government of Canada.[10] Specifically, they state that "*exposure in Canadian homes, schools and offices present no known health risks*." They also state:

> *Health Canada does not consider that any precautionary measures are needed regarding daily exposures to EMFs at ELFs. There is no conclusive evidence of any harm caused by exposures at levels found in Canadian homes and schools, including those located just outside the boundaries of power line corridors.*

The International Committee on Non-Ionizing Radiation Protection (ICNIRP) revised its guidelines for ELF EMF exposure in 2010. As part of the guideline setting process, ICNIRP also reviewed the evidence related to long-term health effects, and concluded the following:

> *The literature on chronic effects of ELF fields has been evaluated in detail by individual scientists and scientific panels. WHO's cancer research institute, IARC (International Agency for Research on Cancer) evaluated ELF magnetic fields in 2002 and classified them in category 2B, which translates to "possibly carcinogenic to humans." The basis for this classification was the epidemiologic results on childhood leukemia. It is the view of ICNIRP that the currently existing scientific evidence that*

[9] http://www.who.int/peh-emf/about/WhatisEMF/en/index1.html (accessed on April 9, 2015).

[10] http://healthycanadians.gc.ca/healthy-living-vie-saine/environment-environnement/home-maison/emf-cem-eng.php (accessed on April 10, 2015).

> *prolonged exposure to ELF magnetic fields is causally related with an increased risk of childhood leukemia is too weak to form the basis for exposure guidelines* (ICNIRP 2010, p. 824).

In March 2015, the European Union's Scientific Committee on Emerging and Newly-Identified Health Risks (SCENIHR) updated its previous review on EMF that included reviews of ELF EMF fields. The conclusions of the SCENIHR review are consistent with the conclusions expressed by the WHO, ICNIRP, and Health Canada. The SCENIHR review did not conclude that the available scientific evidence confirms a causal link between any adverse health effects (including both cancer and non-cancer health outcomes) and EMF exposure. With respect to childhood leukemia epidemiologic results, the review concludes that:

> … *no mechanisms have been identified and no support is existing from experimental studies that could explain these findings, which, together with shortcomings of the epidemiological studies prevent a causal interpretation* (SCENIHR, 2015, p. 7).[11]

The following section reviews the current consensus of these organizations related to particular health outcomes, including childhood cancers (leukemia and brain cancer), adult cancers (brain, lymphohematopoietic, and breast), neurodegenerative diseases, and reproductive effects. For reference, Appendix 3 provides a listing of epidemiologic studies published since the time of the WHO 2007 review.

[11] http://ec.europa.eu/health/scientific_committees/emerging/docs/scenihr_o_041.pdf (accessed April 10, 2015).

4. Current Consensus on Specific Health Outcomes

Childhood leukemia

The incidence rate of leukemia in children is approximately 3 per 100,000 per year, making it a relatively rare cancer, and in the vast majority of cases, the cause is unknown. The only identified causes of childhood leukemia include certain genetic diseases, chemotherapeutic agents, and ionizing radiation from sources such as maternal x-rays during pregnancy, but these account for only a very small percentage of cases. Since so little is known about the cause of this disease, many exposures have been investigated, including infectious agents and environmental exposures such as pesticides, solvents, pollution, and magnetic fields, but no clear patterns have emerged. Suggestive data exists for the role of infections in promoting leukemia in already susceptible children, but the research is inadequate so conclusions about this possible cause are not definitive.

Since 1979, epidemiologic studies conducted in the United States, Canada, Europe, New Zealand, and Asia have evaluated the relationship between childhood leukemia and some proxy of magnetic-field exposure. Independently, these studies did not show a clearly consistent association between magnetic fields and childhood leukemia. In 2002, the IARC conducted a comprehensive review of the scientific research related to ELF EMF to evaluate the strength of the evidence in support of carcinogenicity. Although some of the largest and most methodologically sound case-control studies at the time that directly estimated magnetic-field exposure through long-term personal measurements (Linet et al., 1997; McBride et al., 1999; UKCCS, 1999, 2000) reported no consistent associations, the IARC expert panel noted that, when studies with the relevant information were combined in a pooled analysis (Ahlbom et al., 2000; Greenland et al., 2000),[12] a statistically significant two-fold association was observed between childhood leukemia and estimated exposure to high, average levels of magnetic fields (i.e., greater than 3-4 mG of average 24- and 48-hour exposure). This was classified as "limited evidence" in support of carcinogenicity, falling short of "sufficient evidence" because chance,

[12] Pooled and meta-analyses combine data from the original studies to calculate a summary estimate of the association. Pooled analyses combine the actual raw data from the original studies, while meta-analyses combine the measure of association based on published data from the studies.

bias, and confounding could not be ruled out with "reasonable confidence." Based on this "limited" evidence for an association, the IARC classified magnetic fields as "possibly carcinogenic," a category that describes exposures with limited epidemiologic evidence and inadequate evidence from *in vivo* studies. The classification "possibly carcinogenic" was confirmed by the WHO in June 2007.

Researchers have not concluded, however, that the weak association between childhood leukemia and magnetic fields is causal in nature because the studies are of insufficient quality to rule out the role that chance, bias (e.g., due to exposure misclassification or differential selection and participation of study subjects), and confounding may have on the observed statistical association with "reasonable confidence." As described in Section 2, statistical associations are a measure of how disease and exposure estimates vary together in a specific population, but do not indicate that two factors are causally related. Conclusions about causality are made only when strong epidemiologic data that have confidently ruled out that chance, bias, or confounding played a role in the statistical association and are consistent with the experimental animal data from *in vivo* research. In their 2007 report, the WHO concluded that, while chance is an unlikely explanation, bias arising from uncertainties in exposure (i.e., misclassification) and non-participation of highly-exposed controls (i.e., selection bias) is likely.

Although the WHO report (2007) identified confounding as an unlikely explanation for the statistical association, the reviewers could not rule out its influence because so little is known about the causes of childhood leukemia. Since transmission line rights-of-way are often built along highways, children who live near power lines may also be likely to live near highways. If pollutants from traffic emissions were a cause of childhood leukemia, the association between residential distance to power lines and childhood leukemia could be the result of pollutants from traffic, not magnetic fields from transmission lines. While this is a plausible theory, the research on traffic emissions and childhood leukemia is inconsistent and weak.

A number of epidemiologic studies related to childhood leukemia have been published since the WHO report, but these have failed to explain the statistical association between estimates of high average exposure to magnetic fields (i.e., greater than 3-4 mG) and childhood leukemia.[13] Most

[13] A list of epidemiologic studies published following the WHO report is provided in Appendix 2.

notably, Kheifets et al. (2010a) conducted a pooled analysis of studies published between 2000 and 2010 that was intended to mirror the earlier pooled analyses of studies published between 1974 and 1999 (Ahlbom et al., 2000; Greenland et al., 2000). Kheifets et al. identified six studies for the main analysis that met their inclusion criteria (i.e., population-based studies of childhood leukemia that measured or calculated magnetic fields inside a home). A large number of cases were identified by Kheifets et al. (n=10,865), but a relatively small number of cases (n=23) were classified in the highest exposure category (>3 mG). A positive association was reported (OR=1.44), but it was weaker than the previous pooled estimates and not statistically significant (95% CI=0.88–2.36); a non-significant dose-response relationship was described.

Several recently published epidemiologic studies that examined residential proximity to power lines and childhood leukemia risk in France, the United Kingdom, and Denmark provided no new evidence for an association, and overall the new results have not changed the preponderance of the available evidence. A French study (Sermage-Faure et al., 2013) used geocoded information on residential addresses of childhood leukemia cases and controls and power line locations. Overall no association was observed between childhood leukemia risk and residential proximity to high voltage transmission lines. The authors, however, also reported a statistically not significant association in a sub-analysis within 50 meters of 225-400 kV lines based on a small number of cases (n=9). A Danish study (Pedersen et al., 2014) included 1,698 childhood leukemia cases and 3,396 healthy control children and assessed their residential proximity to the nearest 132 kV, 220 kV, and 400 kV power lines; the authors reported no statistically significant association between risk and residential proximity to these transmission lines. In the largest study to date, Bunch et al. (2014) provided an extension and update to an earlier study in the United Kingdom (Draper et al., 2005). In total they included over 53,000 childhood cancer cases and over 66,000 healthy control children and reported no overall association with residential proximity to 132 kV, 275 kV, and 400 kV power lines for leukemia or any other cancer among children. The statistical association with distance that was reported in the earlier Draper et al. (2005) study was not apparent in the extended analysis. The most recent case-control study on childhood leukemia published from Italy (Salvan et al., 2015) reported no association between risk of disease and measured magnetic-field exposure in the children's bedrooms.

A few studies have also estimated whether survival and relapse among cases of childhood leukemia may be affected by exposure to ELF EMF following diagnosis. While earlier and smaller studies reported weak associations (Foliart et al., 2006; Svendsen et al., 2007), a large pooled analysis (Schüz et al., 2012) that included exposure and clinical data on more than 3,000 cases of childhood leukemia from Canada, Denmark, Germany, Japan, the United Kingdom, and the United States reported no association between magnetic-field exposure and overall survival or relapse of disease in children with leukemia after diagnosis.

Following up on research recommendations by the WHO, methodological research also has been conducted to determine the role that confounding, exposure misclassification, or control selection bias may have on the observed association. [14] While some of the findings suggest that control selection bias is operating to some extent, more research is required to further evaluate the role of control selection bias and confounding, and overall the earlier reported associations remain unexplained.

None of these recent studies represent sufficiently strong methodological improvements, nor do the findings display causal patterns (i.e., exposure-response, consistency, and strength) or provide new insights to alter previous conclusions that the epidemiologic evidence related to magnetic fields and childhood leukemia is limited. Chance, confounding, and several sources of bias cannot be ruled out as an explanation for the observed statistical association. The lack of evidence from *in vivo* research, overall, argues against a causal interpretation, as it has been concluded by the recent SCENIHR report (2015), as well.

Childhood brain cancer

Similar to childhood leukemia, the causes of childhood brain cancer are relatively unknown. Only two causes—radiotherapy for the treatment of other cancers and a particular genetic mutation—have been identified. Far fewer studies have been published on magnetic fields and

[14] Control selection bias refers to a particular type of bias that occurs in case-control studies. If the characteristics of the control group differ from the characteristics of the case group in a way that is related to exposure, the measured statistical association will not represent a true relationship. In the case of magnetic fields and childhood leukemia, researchers are concerned that, because of factors that affect participation in a study, the control group may have a higher socio-economic status than the case group and, as a result, lower magnetic field exposures.

childhood brain cancer than studies on childhood leukemia. The WHO report described the results of these studies as inconsistent and limited by small sample size and recommended that a meta-analysis of the data related to childhood brain cancer and magnetic-field exposure be performed.

The meta- and pooled analyses conducted in response to the WHO's recommendation provided no support for an association (Mezei et al., 2008; Kheifets et al., 2010b). While the meta-analysis was consistent with a very weak association between estimated average exposures greater than 3-4 mG and childhood brain cancer, the association was not statistically significant (i.e., not distinguishable from chance). The pooled analysis including over 8,000 cases of childhood brain cancer from 10 studies showed no consistent risk increase with ELF EMF exposure estimates. The authors concluded that the analyses provide little evidence for a relationship between magnetic fields and childhood brain cancer. Recent studies on the risk of childhood brain cancer related to residential proximity to power lines (Bunch et al., 2014) and pre- and post-conception parental ELF EMF exposure (Hug et al., 2010) do not provide strong evidence of a risk and add little to the existing body of inconsistent literature in this area. Thus, the evidence related to childhood brain cancer and magnetic-field exposure remains inadequate.

Adult brain and lymphohematopoietic cancers

The WHO and other agencies previously classified studies of these cancer types as inadequate, weak, and seriously limited by methods used for exposure assessment. Recent studies have reduced possible exposure misclassification by improving exposure assessment methods and attempted to clarify inconsistencies by updating studies and conducting meta-analyses of recently published studies. Despite these advancements, however, no consistent association has been observed. A meta-analysis, conducted in response to research recommendations of the WHO, reported a small and statistically significant increase of leukemia and brain cancer in relation to the highest estimate of magnetic-field exposure in the individual studies (Kheifets et al., 2008). Several findings, including lower observed risk in more recent and methodologically more rigorous studies, and inconsistent patterns across cancer subtypes, however, led the authors to conclude that magnetic-field exposure is not likely to be responsible for the observed associations. Several recent epidemiologic studies of adult brain cancer and leukemia in relation

to residential proximity to power lines (Marcilio et al., 2011; Elliott et al., 2013) and occupational exposure to ELF EMF (Sorahan, 2012; Koeman et al., 2014; Turner et al., 2014) reported no consistent associations. While an association cannot be *entirely* ruled out because of the remaining deficiencies in exposure assessment methods, the current database of studies provides weak evidence of an association between magnetic fields and adult brain and lymphohematopoietic cancers.[15]

Breast cancer

Following the conclusion of the WHO in 2007 that there was strong evidence against a relationship between exposure to magnetic fields and breast cancer, epidemiologic research related to ELF EMF and breast cancer became of limited priority. Nevertheless, some recent large scale EMF epidemiologic studies also have included breast cancer as an outcome their analyses. Researchers in the United Kingdom have examined residential proximity to high voltage transmission lines and breast cancer development in their case-control study that included over 29,000 cases of female breast cancers, diagnosed between 1974 and 2008, and over 79,000 controls (Elliott et al., 2013). Risk of female breast cancer was not associated with distance to transmission lines or with calculated exposure to magnetic fields. Three recent epidemiologic studies investigated the potential relationship between occupational EMF exposure and breast cancer (Sorahan 2012; Li et al., 2013; Koeman et al., 2014). Sorahan (2012) investigated incidence of cancer among more than 80,000 electricity generation and transmission workers in the United Kingdom between 1973 and 2008. No statistically significant increased risk for breast cancer was reported among either men or women in association with estimates of potential occupational exposures, such as length of employment, industry sector or type of work. Li et al. (2013) studied breast cancer development in a case-control study among more than 260,000 female textile workers in China. No association between occupational exposure to magnetic fields and breast cancer was reported, regardless of age at diagnosis or histological type. Koeman et al. (2014) examined cancer incidence in a cohort of about 120,000 Dutch men and women over an average 17-year period. Risk of breast cancer showed no association with

[15] A consensus statement by the National Cancer Institute's Brain Tumor Epidemiology Consortium confirms this statement. They classified residential power frequency EMF in the category "probably not risk factors" and described the epidemiologic data as "unresolved" (p. 1958, Bondy et al., 2008).

estimated occupational exposure to EMF or length of employment in exposed jobs. Thus, results of recent epidemiologic studies of breast cancer that evaluated ELF EMF exposure in the subjects' homes or workplaces reported no associations and provided further support for the conclusion of the WHO in 2007. A recent review by SCENIHR (2015) also concluded that, overall, studies on "adult cancers show no consistent associations."

Neurodegenerative diseases

The research on ELF EMF and neurodegenerative diseases, including Alzheimer's disease and amyotrophic lateral sclerosis (ALS), also known as Lou Gehrig's disease, did not begin until around 1995, later than other areas of ELF EMF research. The WHO report stated that there is inadequate data in support of an association between magnetic fields and any of the neurodegenerative diseases. Alzheimer's disease, in particular, presents a unique challenge to epidemiologists because of the nature of the disease. Disease onset is typically late in life and is insidious in nature, and it may be misdiagnosed as other neurodegenerative conditions, such as cerebrovascular disease. Misclassification of disease is, therefore, common and since the disease may be present well before symptoms appear, the etiologically relevant time period, if any, is difficult to define, potentially resulting in incorrect estimates of exposure.

Some of the earlier studies of Alzheimer's disease that tended to rely on clinics and treatment centers for case identification also reported associations with estimated occupational exposure to ELF EMF. The main limitation of these studies was reliance on recall to assess occupational exposure to ELF EMF, which is particularly prone to bias especially for diseases of cognitive decline. Later studies, including those of electric company workers, showed mixed results and could not consistently confirm an association. A major limitation of these studies was their reliance on death certificates (mortality data) for case identification. Alzheimer's disease, in particular, is subject to severe underreporting on death certificates, which may potentially result in significant bias in these studies.

A recently published meta-analysis on occupational exposure to magnetic fields and neurodegenerative disease suggested that Alzheimer's disease risk was moderately associated with estimated magnetic-field levels (Vergara et al., 2013). According to the authors, however,

this association might be, at least partially, explained by publication bias due to more likely publication of positive studies, as indicated by their statistical analyses. ALS was moderately associated with exposure estimates in the meta-analysis, but this association was stronger in studies that used occupational titles than in studies using estimates of magnetic fields. This led the authors to conclude that exposure to magnetic fields probably did not explain the observed association for ALS.

Recent studies have also investigated residential proximity to power lines in relation to neurodegenerative diseases. While two mortality studies in Switzerland and Brazil (Huss et al., 2009; Marcilio et al., 2011) showed mixed results, a study from Denmark (Frei et al., 2013) that relied on hospital discharge records to identify newly diagnosed cases reported no associations with residential distance to power lines. While the identification of newly diagnosed cases in the Danish study represents a significant methodological improvement compared to mortality studies, the use of distance, which is not a good proxy for magnetic-field exposure, remains a main limitation of these studies. Several studies have also followed up on the hypothesis that the observed association with ALS might be due to exposure to electric shocks during work rather than exposure to EMF. These studies, however, failed to provide convincing evidence for an association with electric shocks (van der Mark et al., 2014; Vergara et al., 2015).

The recent epidemiologic studies do not alter the conclusion that there is "inadequate" data on Alzheimer's disease and ALS and overall do not provide support for an association. There is currently no body of *in vivo* research to suggest an effect.

Reproductive and developmental effects

Very little epidemiologic research has been published in this area. The WHO categorized this data as inadequate, stating that there is some evidence in support of peak magnetic-field exposures and miscarriage, but there were methodological issues with this research (Li et al., 2002; Lee et al., 2002; Savitz, 2002). The results from methodological studies support the potential role of bias in the studies of peak magnetic-field exposure and miscarriage (Mezei et al. 2006; Savitz et al., 2006; Lewis et al., 2015). There continues to be no convincing epidemiologic evidence linking magnetic-field exposure to the risk of miscarriage. Publications

from one research group have suggested associations between maternal exposure to EMF during pregnancy and various health outcomes (e.g., asthma and obesity) in the offspring (Li et al., 2011; Li et al., 2012). These findings, however, lack plausible biological hypotheses and were not independently replicated by other research groups. Overall, the recent epidemiologic research on reproductive or developmental effects remains inadequate.

5. Standards and Guidelines

Since the scientific organizations that regularly review research on ELF EMF have determined there are no known long-term health effects from exposure, no standards or guidelines limiting exposure to ELF EMF based on long-term health effects have been recommended. Accordingly, there are no national standards in Canada or the United States limiting exposures to ELF EMF based on long-term or other health effects. Similarly, there are no provincial or territorial EMF exposure limits in Canada, or state limits in the United States that are based on the determination that EMF causes adverse health effects.

Two of the scientific organizations that review the scientific literature on ELF EMF (ICNIRP and the International Commission on Electromagnetic Safety [ICES]) have published guidelines limiting exposure to very high levels of ELF EMF based on the avoidance of immediate short-term health effects, which include biological responses such as perception, annoyance, and the stimulation of nerves and muscles. Following a thorough review of the scientific literature related to short- and long-term adverse effects, the ICNIRP published revised guidelines in December 2010 to replace their 1998 ELF EMF guidelines. The document recommended no change to ICNIRP's assessment of the scientific evidence; as before, research related to long-term health effects does not provide sufficient evidence to warrant a change to the exposure guidelines. ICNIRP did, however, raise the residential screening value for magnetic fields from 833 to 2,000 mG. The occupational screening value of 4,200 mG (ICNIRP, 1998; ICNIRP, 2010) was not changed.

The ICES also recommends limiting exposures at high levels because of the risk of immediate stimulation responses, although their guidelines are set well above ICNIRP's guidelines (ICES, 2002).[16] In almost all cases, transmission lines meet these magnetic-field exposure guidelines, although some appliances do not.

[16] The ICES is "responsible for development of standards for the safe use of electromagnetic energy in the range of 0 Hz to 300 GHz relative to the potential hazards of exposure of humans, volatile materials, and explosive devices to such energy, standards for products that emit electromagnetic energy by design or as a by-product of their operation, and standards for environmental limits."

Table 2. Reference levels for whole body exposure to 60-Hz fields: general public

Organization recommending limit	Magnetic fields	Electric fields
ICNIRP reference level (2010)	2,000 mG	4.2 kV /m
ICES maximum permissible exposure (2002)	9,040 mG	5 kV/m 10 kV/m[a]

[a] This is an exception within transmission line ROWs because people do not spend a substantial amount of time in ROWs and very specific conditions are needed before a response is likely to occur (i.e., a person must be well insulated from ground and must contact a grounded conductor).

6. Precautionary Measures

Public concern about the possible adverse effects of exposure to magnetic fields has been addressed by some agencies, such as the WHO and the National Institute of Environmental Health Sciences, by recommending measures that utilize the precautionary principle. The precautionary principle is a policy that emerged in Europe in the 1970s to address perceived adverse environmental effects. Under the precautionary principle, measures are taken to reduce exposures that are proportional to the perceived level of risk as identified by standard scientific methods. In the case of ELF EMF, since the data suggesting adverse health effects are weak, precautionary measures have been recommended that are not costly and are easy to implement. For example, moving appliances away from sleeping areas is one no cost way to reduce exposure. The WHO recommended the following precautionary approaches in their 2007 report (pp. 372-373):

- Policy-makers should establish guidelines for ELF field exposure for both the general public and workers [related to short-term stimulation effects]. The best source of guidance for both exposure levels and the principles of scientific review are the international guidelines.
- Policy-makers should establish an ELF EMF protection programme that includes measurements of fields from all sources to ensure that the exposure limits are not exceeded either for the general public or workers.
- Provided that the health, social, and economic benefits of electric power are not compromised, implementing very low-cost precautionary procedures to reduce exposures is reasonable and warranted.
- Policy-makers and community planners should implement very low-cost measures when constructing new facilities and designing new equipment including appliances.
- Changes to engineering practice to reduce ELF exposure from equipment or devices should be considered, provided that they yield other additional benefits, such as greater safety, or involve little or no cost.

- When changes to existing ELF sources are contemplated, ELF field reduction should be considered alongside safety, reliability, and economic aspects.
- Local authorities should enforce wiring regulations to reduce unintentional ground currents when building new or rewiring existing facilities, while maintaining safety. Proactive measures to identify violations or existing problems in wiring would be expensive and unlikely to be justified.
- National authorities should implement an effective and open communication strategy to enable informed decision-making by all stakeholders; this should include information on how individuals can reduce their own exposure.
- Local authorities should improve planning of ELF EMF-emitting facilities, including better consultation between industry, local government, and citizens when siting major ELF EMF-emitting sources.
- Government and industry should promote research programmes to reduce the uncertainty of the scientific evidence on the health effects of ELF field exposure.

In Canada, the FPTRPC's approach to precautionary measures is similar to the recommendations made by the WHO. The FPTRPC stated, "In the context of power-frequency EMFs, health risks to the public from such exposures have not been established; therefore, it is the opinion of the FPTRPC that any precautionary measures applied to power lines should favour low cost or no cost options" (FPTRPC, 2008). The current position of the government is "Health Canada does not consider that any precautionary measures are needed regarding daily exposures to EMFs at ELFs. There is no conclusive evidence of any harm caused by exposures at levels found in Canadian homes and schools, including those located just outside the boundaries of power line corridors."[17]

[17] http://healthycanadians.gc.ca/healthy-living-vie-saine/environment-environnement/home-maison/emf-cem-eng.php (accessed on April 10, 2015).

7. Other Research Topics

Livestock, wildlife, and crops

High-voltage and ultra-high-voltage transmission lines often traverse farmland, forests, and woodlands that have substantial populations of both domestic and wild animals and a wide variety of crops and plants. Prompted by concerns about the effects of EMF through these areas, research has been conducted since the 1970s on the possible effects of EMF on the health, behavior, and productivity of a number of species, including livestock and a range of wild animals and insects, as well as the possible effects on farm crops and natural flora.

Livestock, most systematically cattle, were the focus of both observational and experimental EMF research. Farm surveys and observational studies of grazing cattle conducted near 765-kV and 400-kV transmission lines reported no consistent differences in behavior, fertility, or productivity between animals near or farther away from the lines (Busby et al., 1974; Ware, 1974; Amstutz and Miller, 1980; Algers et al., 1982; Hennichs, 1982; Algers and Hennichs, 1985; Algers and Hultgren, 1986, 1987). A series of controlled experiments to evaluate potential effects of EMF exposure on various physiological parameters of dairy cattle were conducted by Canadian researchers (e.g., Rodriguez et al., 2002, 2003, 2004; Burchard et al., 2003, 2004, 2007). Electric-field exposures up to 10 kV/m and magnetic-field exposures up to 300 mG were used in the experiments that evaluated measures of reproductive function (e.g., estrus cycle and gestational hormone levels), quality and quantity of milk production, feed intake, and various hormone levels. While some variability between exposed and control cows was observed in some of the examined parameters, these differences were typically within a few percent and were within physiological ranges. Overall, no consistent differences between exposed and unexposed animals were observed in various measures of milk yield, hormone concentrations, and other parameters. As the authors concluded in one of their papers, “[t]he absence of abnormal clinical signs and the absolute magnitude of the significant changes detected during MF [magnetic field] exposure, make it plausible to preclude any major animal health hazard” (Burchard et al., 2007, p. 471).

Researchers have also evaluated hormone levels, immunological parameters, weight gain, wool production, and developmental milestones in sheep and reproduction in swine (McCoy and Hefeneider, 1993; Lee et al., 1993; Thompson et al., 1995; Hefeneider et al., 2001; Mahmoud and Zimmerman, 1984). Overall, no consistent or replicated changes were reported in the measured parameters that correlated with EMF exposure.

Wildlife in the vicinity of high voltage transmission lines has also been studied. Movement pattern of elk and deer near 500-kV lines, and migration, range use, grazing pattern, and behavior of wild and domesticated reindeer near high voltage transmission lines were examined (Goodwin, 1975; Picoton et al., 1985; Reimers et al., 2007; Flydal et al., 2009). The authors of these studies concluded that the presence of transmission lines did not result in consistent changes in the behavior of the studied large mammals.

A large number crops and various plant species have been used to investigate potential beneficial and adverse agricultural effects of EMF. A series of field studies reported on growth of peas and barley near power lines (Rogers et al., 1979, 1980; Warren et al., 1981; Lee and Clark, 1981). Overall, no consistent differences were noted. Researchers also examined field corn, soybeans, wheat, alfalfa, and tobacco, and reported normal plant development near high voltage power lines (Hodges et al., 1975; Hodges and Mitchell, 1984). Controlled experiments were conducted with over 70 plant species, including food, fiber, and feed crops (e.g., alfalfa, field corn, and wheat), weeds, native plants, and several tree species, as part of a research program at Pennsylvania State University (Bankoske et al, 1976; McKee et al, 1978). Plants were exposed to electric-field levels up to 50 kV/m and compared to plants with no exposure to electric fields. No statistically significant differences were observed in seed germination, seedling, seed maturation, biomass production, feed quality, essential element content, leaf area, or longevity. Subsequent experimental studies also investigated radish, mustard, barley, and strawberry, among other plants (Ruzic et al., 1992; Smith et al., 1993; Mihai et al., 1994; Davies, 1996; Potts et al., 1997; Eşitken and Turan, 2004) and reported varying results. Overall, no consistently replicated adverse effects of transmission lines or exposure to EMF on plant development were reported in any of these studies. EMF exposure levels in many of these studies were much higher than levels that could be encountered near high-voltage transmission lines in Alberta.

In summary, the available research results to date do not suggest that magnetic or electric fields (or any other aspect of high-voltage transmission lines, such as audible noise) result in adverse effects on the health, behavior, or productivity of fauna, including livestock such as dairy cows, sheep, pigs, and a variety of other species including small mammals, deer, elk, birds, and bees. Studies were also conducted to evaluate whether EMF could affect crops or plants, but did not suggest any adverse effects on growth or viability.

Implanted Medical Devices

Questions about potential effects that EMF might have on the operation and functioning of pacemakers and other implanted cardiac devices (ICDs) are also commonly raised in relation to high-voltage transmission lines. The heart's rhythm is controlled naturally by electrical signals. When there is a disturbance to this rhythm, a pacemaker or ICD is implanted to restore normal cardiac function. Since the sensing system of these devices is naturally responsive to the heart's electrical signal, other electrical signals can interfere with the normal functioning of pacemakers and ICDs, a phenomenon called electromagnetic interference. Potential sources of EMI include cellular telephones, anti-theft devices in stores, magnetic-resonance imaging machines, slot machines, and certain medical procedures (e.g., radiation therapy, electrocautery, and defibrillation). Experimental tests sometimes have shown subtle effects of strong electric fields on pacemaker operation (Joosten et al., 2009; Korpinen et al., 2012; Tiikkaja et al., 2013), but no case reports of interference with patients' pacemakers by electric or magnetic fields associated with transmission lines have been reported in the literature. Recent inquiries (up until 2014) to The Recalls and Safety Alerts Database of Health Canada's MedEffect™, the Manufacturer and User Facility Device Experience database maintained by the United States Food and Drug Administration, and the Medicines and Healthcare Products Regulatory Agency, the relevant regulatory body in the United Kingdom, have not identified any reports that would suggest episodes where electromagnetic interference occurred with ICDs due to electric or magnetic fields from electric power lines. Transmission line magnetic fields are generally too weak to affect pacemakers, and electric field strength decreases with distance and is shielded by trees, buildings, vehicles, fences, and other objects. Most modern ICDs are now designed and constructed with features (e.g., hermetic shielding by metallic cases, built-in filters, switches, and programmable settings of sensitivity, mode and polarity) that make these devices more immune

to extraneous electrical signals and significantly reduce the potential for interference (Dyrda and Khairy, 2008).

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Appendix 1

Conclusions of the WHO's Environmental Health Criteria 238

Outcome	WHO conclusion or recommendation in 2007
Overall conclusions	"New human, animal, and in vitro studies published since the 2002 IARC Monograph, 2002 [*sic*] do not change the overall classification of ELF as a possible human carcinogen" (p. 347). "Acute biological effects [i.e., short-term, transient health effects such as a small shock] have been established for exposure to ELF electric and magnetic fields in the frequency range up to 100 kHz that may have adverse consequences on health. Therefore, exposure limits are needed. International guidelines exist that have addressed this issue. Compliance with these guidelines provides adequate protection. Consistent epidemiological evidence suggests that chronic low-intensity ELF magnetic field exposure is associated with an increased risk of childhood leukaemia. However, the evidence for a causal relationship is limited, therefore exposure limits based upon epidemiological evidence are not recommended, but some precautionary measures are warranted" (p. 355-6).
Childhood leukemia	"Consistent epidemiological evidence suggests that chronic low intensity ELF magnetic field exposure is associated with an increased risk of childhood leukaemia. However, the evidence for a causal relationship is limited, therefore exposure estimates based upon epidemiological evidence are not recommended, but some precautionary measures are warranted" (p. 355-6).
Childhood brain cancer	The WHO described the data related to childhood brain cancer as inadequate. They stated, "As with childhood leukaemia, a pooled analysis of childhood brain cancer studies should be very informative and is therefore recommended. A pooled analysis of this kind can inexpensively provide a greater and improved insight into the existing data, including the possibility of selection bias and, if the studies are sufficiently homogeneous, can offer the best estimate of risk" (p. 18).
Adult leukemia Adult brain cancer	The WHO concluded, "In the case of adult brain cancer and leukaemia, the new studies published after the IARC monograph do not change the conclusion that the overall evidence for an association between ELF [EMF] and the risk of these disease remains inadequate" (p. 307).
Breast cancer	The WHO concluded, "[w]ith these [recent] studies, the evidence for an association between ELF magnetic field exposure and the risk of female breast cancer is weakened considerably and does not support an association of this kind" (p. 9).

Outcome	WHO conclusion or recommendation in 2007
In vivo cancer research	The WHO concluded "[t]here is no evidence that ELF exposure alone causes tumours. The evidence that ELF field exposure can enhance tumour development in combination with carcinogens is inadequate" (p. 10).
Neurodegenerative diseases	"Overall, the evidence for the association between ELF exposure and ALS is considered inadequate. The few studies investigating the association between ELF exposure and Alzheimer's disease are inconsistent. However, the higher quality studies that focused on Alzheimer morbidity rather than mortality do not indicate an association. Altogether, the evidence for an association between ELF exposure and Alzheimer's disease is inadequate" (p. 206).
Reproductive effects	"On the whole, epidemiological studies have not shown an association between adverse human reproductive outcomes and maternal or paternal exposure to ELF fields. There is some evidence for increased risk of miscarriage associated with measured maternal magnetic field exposure, but this evidence is inadequate" (p. 255).

Appendix 2

Health Canada: It's Your Health – Electric and Magnetic Fields From Power Lines and Electrical Appliances

Health Canada Santé Canada

Your health and safety… our priority. *Votre santé et votre sécurité… notre priorité.*

Electric and Magnetic Fields

Updated: November 2012

Original: November 2001

IT'S YOUR HEALTH

Electric and Magnetic Fields from Power Lines and Electrical Appliances

THE ISSUE

Some people are concerned that daily exposure to electric and magnetic fields (EMFs) may cause health problems.

ELECTRICITY AND ELECTRIC AND MAGNETIC FIELDS (EMFS)

Electricity delivered through power lines is important in today's society. It is used to light homes, prepare food, run computers and operate other household appliances, such as TVs and radios. In Canada, appliances that plug into a wall socket use electric power that flows back and forth at a frequency of 60 cycles per second (60 hertz). The frequency used with the distribution of electricity from power lines and electrical appliances is different than the frequencies used for Wi-Fi, cell phones, and smart meters.

Every time you use electricity and electrical appliances, you are exposed to electric and magnetic fields (EMFs) at extremely low frequencies (ELFs). The term "extremely low" is described as any frequency below 300 hertz. EMFs produced by the transmission and use of electricity belong to this category.

EMFs are invisible forces that surround electrical equipment, power cords, and wires that carry electricity, including outdoor power lines.

- *Electric Fields:* These are formed whenever a wire is plugged into an outlet, even when the appliance is not turned on. The higher the voltage, the stronger the electric field.
- *Magnetic Fields:* These are formed when electric current is flowing within a device or wire. The greater the current, the stronger the magnetic field.

EMFs can occur separately or together. For example, when you plug the power cord for a lamp into a wall socket, it creates an electric field along the cord. When you turn the lamp on, the flow of current through the cord creates a magnetic field. Meanwhile, the electric field is still present.

Canada

POWER LINES AND YOUR HOME

EMFs are strongest when close to their source. As you move away from the source, the strength of the fields fades rapidly. This means you are exposed to stronger EMFs when standing close to a source (e.g., right beside a transformer box or under a high voltage power line), and you are exposed to weaker fields as you move away.

When you are inside your home, the magnetic fields from high voltage power lines and transformer boxes are often weaker than those from household electrical appliances.

Electric fields can be shielded using materials such as metal. Things like buildings and trees—and even the ground when power lines are buried—can block electric fields.

CANADIANS EXPOSURE TO EMFS AT EXTREMELY LOW FREQUENCIES (ELFS)

On a daily basis, most Canadians are exposed to EMFs generated by household wiring, lighting, and any electrical appliance that plugs into the wall, including hair dryers, vacuum cleaners and toasters. In the workplace, common sources of EMFs include computers, air purifiers, photocopiers, fax machines, fluorescent lights, electric heaters, and electric tools in machine shops, such as drills, power saws, lathes and welding machines.

EXPOSURE IN CANADIAN HOMES, SCHOOLS AND OFFICES PRESENT NO KNOWN HEALTH RISKS

There have been many studies on the possible health effects from exposure to EMFs at ELFs. While it is known that EMFs can cause weak electric currents to flow through the human body, the

intensity of these currents is too low to cause any known health effects. Some studies have suggested a possible link between exposure to ELF magnetic fields and certain types of childhood cancer, but at present this association is not established.

The International Agency for Research on Cancer (IARC) has classified ELF magnetic fields as “possibly carcinogenic to humans”. The IARC classification of ELF magnetic fields reflects the fact that some limited evidence exists that ELF magnetic fields might be a risk factor for childhood leukemia . However, the vast majority of scientific research to date does not support a link between ELF magnetic field exposure and human cancers. At present, the evidence of a possible link between ELF magnetic field exposure and cancer risk is far from conclusive and more research is needed to clarify this “possible” link.

Health Canada is in agreement with both the World Health Organization and IARC that additional research in this area is warranted.

REDUCE YOUR RISK

Health Canada does not consider that any precautionary measures are needed regarding daily exposures to EMFs at ELFs. There is no conclusive evidence of any harm caused by exposures at levels found in Canadian homes and schools, including those located just outside the boundaries of power line corridors.

THE GOVERNMENT OF CANADA’S ROLE

Health Canada, along with the World Health Organization, monitors scientific research on EMFs and human health as part of its mission to help Canadians maintain and improve their health.

International exposure guidelines for exposure to EMFs at ELFs have been established by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). These guidelines are not based on a consideration of risks related to cancer. Rather, the point of the guidelines is to make sure that exposures to EMFs do not cause electric currents or fields in the body that are stronger than the ones produced naturally by the brain, nerves and heart. EMF exposures in Canadian homes, schools and offices are far below these guidelines.

FOR MORE INFORMATION

- Health Canada’s Electric and magnetic fields at: www.hc-sc.gc.ca/ewh-semt/radiation/cons/electri-magnet/index-eng.php
- The World Health Organization – Electromagnetic fields and public health:
  - Exposure to extremely low frequency fields at: www.who.int/mediacentre/factsheets/fs322/en/index.html
  - Extremely low frequency at: www.who.int/docstore/peh-mf/publications/facts_press/efact/efs205.html
  - Extremely low frequency fields and cancer at: www.who.int/docstore/peh-emf/publications/facts_press/efact/efs263.html

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FOR INDUSTRY AND PROFESSIONALS

- The International Agency for Research on Cancer (IARC) Volume 80 – Non-Ionizing Radiation, Part 1: Static and Extremely Low-Frequency (ELF) Electric and Magnetic Fields at: http://monographs.iarc.fr/ENG/Monographs/vol80/volume80.pdf
- IARC Carcinogen classifications at: http://monographs.iarc.fr/ENG/Classification/index.php

RELATED RESOURCES

- Health Canada, *It's Your Health*:
  - Safety of Wi-Fi Equipment at: www.hc-sc.gc.ca/hl-vs/iyh-vsv/prod/wifi-eng.php
  - Safety of Cell Phones and Cell Phone Towers at: www.hc-sc.gc.ca/hl-vs/iyh-vsv/prod/cell-eng.php
- For safety information about food, health and consumer products, visit the Healthy Canadians website at: www.healthycanadians.gc.ca
- For more articles on health and safety issues go to the *It's Your Health* web section at: www.health.gc.ca/iyh

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Appendix 3

Relevant Epidemiology Studies Published after the WHO Report by Health Outcome

Relevant epidemiology studies published after the WHO report by health outcome

Authors	Study Title	Journal
	Childhood Leukemia	
Abdul Rahman HI, Shah SA, Alias H, et al.	A case-control study on the association between environmental factors and the occurrence of acute leukemia among children in Klang Valley, Malaysia.	Asian Pac J Cancer Prev 9:649-652, 2008
Bunch KJ, Keegan TJ, Swanson J, Vincent TJ, Murphy MF.	Residential distance at birth from overhead high-voltage powerlines: childhood cancer risk in Britain 1962-2008.	Br J Cancer 110: 1402-1408, 2014.
Fezei AA and Arabi MA.	Acute childhood leukemias and exposure to magnetic fields generated by high voltage overhead power lines – a risk factor in Iran	Asian Pac J Cancer Prev 8:69-72, 2007
Foliart DE, Pollack BH, Mezei G.	Magnetic field exposure and long-term survival among children with leukaemia	Br J Cancer 94:161-164, 2006
Foliart DE, Mezei G, Iriye R, et al.	Magnetic field exposure and prognostic factors in childhood leukemia	Bioelectromagnetics 28:69-71, 2007
Greenland S and Kheifets L.	Leukemia attributable to residential magnetic fields: Results from analyses allowing for study biases	Risk Anal 26:471-482, 2006
Hug K, Grize L, Seidler A, et al.	Parental occupational exposure to extremely low frequency magnetic fields and childhood cancer: a German case-control study	Am J Epidemiol 171:27-35, 2010
Kheifets L, Ahlbom A, Crespi CM, et al.	Pooled analysis of recent studies on magnetic fields and childhood leukaemia	Br J Cancer 103:1128-1135, 2010
Kroll ME, Swanson J, Vincent TJ, Draper GJ.	Childhood cancer and magnetic fields from high-voltage power lines in England and Wales: a case-control study	Br J Cancer 103:1122-1127, 2010
Malagoli C, Fabbi S, Teggi S, et al.	Risk of hematological malignancies associated with magnetic fields exposure from power lines: a case control study in two municipalities in northern Italy.	Environ Health 9:16, 2010
Maslanyj M, Simpson J, Roman E, et al.	Power frequency magnetic fields and risk of childhood leukaemia: Misclassification of exposure from the use of the 'distance from power line' exposure surrogate	Bioelectromagnetics 30:183-188, 2009
Mejia-Arangure JM, Fajardo-Guitierrez A, Perez-Saldivar ML, et al.	Magnetic fields and acute leukemia in children with Down syndrome	Epidemiology 18:158-161, 2007
Mezei G and Kheifets L.	Selection bias and its implications for case-control studies: A case study of magnetic field exposure and childhood leukaemia	Int J Epidemiol 35:397-406, 2006
Mezei G, Spinelli JJ, Wong P, et al.	Assessment of selection bias in the Canadian case-control study of residential magnetic field exposure and childhood leukemia	Epidemiology 29:424-430, 2008a
Pearce MS, Tupitsyn AN, Legros A, et al.	Paternal occupational exposure to electro-magnetic fields as a risk factor for cancer in children and young adults: A case-control study from the North of England	Pediatr Blood Cancer 49:280-286, 2007
Pedersen C, Raaschou-Nielsen O, Rod NH, Frei P, Poulsen AH, Johansen C, Schuz J	Distance from residence to power line and risk of childhood leukemia: a population-based case-control study in Denmark	Cancer Causes Control 25: 171-177, 2014
Sermage-Faure C, Demoury C, Rudant J, et al.	Childhood leukaemia close to high-voltage power lines--the Geocap study, 2002-2007	Br J Cancer 108: 1899-1906, 2013
Schüz J, Svendsen AL, Linet MS, et al.	Nighttime exposure to electromagnetic fields and childhood leukemia: An extended pooled analysis	Am J Epidemiol 166:263-269, 2007

Authors	Study Title	Journal
Schüz J, Grell K, Kinsey S, Linet MS, et al.	Extremely low-frequency magnetic fields and survival from childhood acute lymphoblastic leukemia: an international follow-up study	Blood Cancer J 2: e98, 2012
Svendson AL, Weihkopf T, Kaatsch P, et al.	Exposure to magnetic fields and survival after diagnosis of childhood leukemia: An extended pooled analysis	Cancer Epidemiol Biomarkers Prev 16:1167-171, 2007
Sohrabi MR, Tarjoman T, Abadi A, et al.	Living near overhead high voltage transmission power lines as a risk factor for childhood acute lymphoblastic leukemia: a case-control study	Asian Pac J Cancer Prev 22:423-427, 2010
Yang Y, Jin X, Yan C, et al.	Case-only of interactions between DNA repair genes (hMLH1, APEX1, MGMT, XRCC1, and XPD) and low frequency electromagnetic fields in childhood acute leukemia	Leukemia & Lymphoma 49:2344-2350, 2008
Childhood Brain Cancer		
Hug K, Grize L, Seidler A, et al.	Parental occupational exposure to extremely low frequency magnetic fields and childhood cancer: a German case-control study	Am J Epidemiol 171:27-35, 2010
Kheifets L, Ahlbom A, Crespi CM, et al.	A pooled analysis of extremely low-frequency magnetic fields and childhood brain tumors	Am J Epidemiol 172:752-761, 2010
Li P, McLaughlin J, Infante-Rivard C.	Maternal occupational exposure to extremely low frequency magnetic fields and the risk of brain cancer in the offspring	Cancer Causes Control 20:945-955, 2009
Mezei G, Spinelli JJ, Wong P, et al.	Residential magnetic field exposure and childhood brain cancer: a meta-analysis	Am J Epidemiol 167:1504-1510, 2008b
Saito T, Nitta H, Kubo O, et al.	Power-frequency magnetic fields and childhood brain tumors: a case-control study in Japan	J Epidemiol 20:54-61, 2010
Adult Brain Cancer and Lymphohematopoietic Cancers		
Coble JB, Dosemeci M, Stewart PA, et al.	Occupational exposure to magnetic fields and the risk of brain tumors	Neuro Oncol 11:242-249, 2009
Elliott P, Shaddick G, Douglass M, et al.	Adult cancers near high-voltage overhead power lines	Epidemiology 24: 184-190, 2013
Forssén UM, Lonn S, Ahlbom A.	Occupational magnetic field exposure and the risk of acoustic neuroma	Am J Ind Med 49:112-118, 2006
Gobba F, Bargellini A, Scaringi M, et al.	Extremely low frequency-magnetic fields (ELF-EMF) occupational exposure and natural killer activity in peripheral blood lymphocytes	Sci Total Environ 15:407:1218-1223, 2009
Johansen C, Raaschou-Nielsen O, Olsen JH, et al.	Risk for leukaemia and brain and breast cancer among Danish utility workers: A second follow-up.	Occup Environ Med 64:782-784, 2007
Karipidis K, Benke G, Sim M, et al.	Occupational exposure to power frequency magnetic fields and risk of non-Hodgkin lymphoma.	Occup Environ Med 64:25-29, 2007a
Karipidis K, Benke G, Sim MR, et al.	Occupational exposure to low frequency magnetic fields and the risk of low grade and high grade glioma	Cancer Causes Control 18:305-313, 2007b
Kheifets L, Monroe J, Vergara X, et al.	Occupational electromagnetic fields and leukemia and brain cancer: An update to two meta-analyses	JOEM 50:677-688, 2008
Koeman T, van den Brandt PA, et al.	Occupational extremely low-frequency magnetic field exposure and selected cancer outcomes in a prospective Dutch cohort	Cancer Causes Control 25: 203-214, 2014
Lowenthal RM, Tuck DM, Bray IC.	Residential exposure to electric power transmission lines and risk of lymphoproliferative and myeloproliferative disorders: A case-control study	Intern Med J 37:614-619, 2007

Authors	Study Title	Journal
Marcilio I, Gouveia N, Pereira Filho ML, Kheifets L	Adult mortality from leukemia, brain cancer, amyotrophic lateral sclerosis and magnetic fields from power lines: a case-control study in Brazil	Rev Bras Epidemiol 14: 580-588, 2011
Richardson DB, Terschuren C, Hoffmann W.	Occupational risk factors for non-Hodgkin's lymphoma: A population-based case-control study in northern Germany	Am J Ind Med 51:258-268, 2008
Röösli M, Lörtscher M, Egger M, et al.	Leukaemia, brain tumors and exposure to extremely low frequency magnetic fields: Cohort study of Swiss railway employees	Occup Environ Med 64:553-559, 2007a
Sorahan T.	Cancer incidence in UK electricity generation and transmission workers, 1973-2008	Occup Med (Lond) 62: 496-505, 2012
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