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July 7, 2022

Melanie A. Bachman, Esq.
Executive Director
Connecticut Siting Council
10 Franklin Square
New Britain, CT 06051

Re: Docket No. 3B - The United Illuminating Company Amended Certificate of Environmental Compatibility and Public Need for Replacement of a Portion of the Existing Derby – Shelton 115-kV Electric Transmission Line Facility

Dear Ms. Bachman:

Enclosed for filing with the Connecticut Siting Council ("Council") is a report entitled "Summary of Health Research Related to Extremely Low Frequency Electric and Magnetic Fields, December 2017 through January 2022" prepared by Exponent, Inc. for The United Illuminating Company (the "Company") (the "2022 Report"). The Company asks that the Council take administrative notice of the 2022 Report and that it replace Exponent's 2017 report that is document #63 on the Administrative Notice List in this docket.

An original and fifteen (15) copies of this filing will be mailed via first-class mail to the Council.

Should you have any questions regarding this letter, please do not hesitate to contact me.

Very truly yours,

Bruce L. McDermott

Enclosures

cc: Service List

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Summary of Health Research Related to Extremely Low Frequency Electric and Magnetic Fields

December 2017 through January 2022

Summary of Health Research Related to Extremely Low Frequency Electric and Magnetic Fields

December 2017 through January 2022

Prepared for

The United Illuminating Company
180 Marsh Hill Rd.
Orange, CT 06477

Prepared by

Exponent, Inc.
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July 6, 2022

Contents

Limitations

Exponent, Inc. (Exponent), prepared this summary report on the status of research related to extremely low frequency electric- and magnetic-field exposure and health at the request of the United Illuminating Company (UI), a subsidiary of Avangrid. The findings presented herein are made to a reasonable degree of scientific certainty. Exponent reserves the right to supplement this report and to expand or modify opinions based on review of additional material as it becomes available, through any additional work, or review of additional work performed by others.

The scope of services performed during this investigation may not adequately address the needs of other users of this report, and any re-use of this report or its findings, conclusions, or recommendations presented herein are at the sole risk of the user. The opinions and comments formulated during this assessment are based on observations and information available at the time of the investigation. No guarantee or warranty as to future life or performance of any reviewed condition is expressed or implied.

Acronyms and Abbreviations

µT	microtesla
ALS	amyotrophic lateral sclerosis
aOR	adjusted odds ratio
B-ALL	B-lineage acute lymphoblastic leukemia
CI	confidence interval
CNS	central nervous system
DMBA	7,12-dimethylbenz[a]anthracene
EHC	Environmental Health Criteria
EFHRAN	European Health Risk Assessment Network on Electromagnetic Fields Exposure
ELF	extremely low frequency
EMF	electric and magnetic fields
ENU	ethylnitrosourea
EPA	U.S. Environmental Protection Agency
Exponent	Exponent, Inc.
G	gauss
Hz	hertz
ICES	International Committee on Electromagnetic Safety
ICNIRP	International Commission on Non-Ionizing Radiation Protection
JEM	job exposure matrix
kV	kilovolt
kV/m	kilovolts per meter
mG	milligauss
MND	motor neuron disease
NRPB	National Radiological Protection Board
NTP	National Toxicology Program
OR	odds ratio
ROW	right of way
sRR	summary risk ratio
TWA	time weighted average
UI	United Illuminating
V/m	volts per meter

Executive Summary

This report was prepared to address the topic of extremely low frequency (ELF) electric and magnetic fields (EMF) and health at the request of UI.

Both natural and man-made sources of EMF surround us in our daily lives; an overview of the nature and sources of EMF in our environment are summarized in Section 1 (*Electric and Magnetic Fields*).

Guidance on the possible health risks of all types of exposures comes from health risk assessments or systematic weight-of-evidence evaluations of the cumulative literature on a particular topic conducted by expert panels assembled by scientific and government organizations. The standard scientific process for evaluating a body of research to understand the potential health implications of exposure is described in Section 2 (*Scientific Review Process*). The World Health Organization (WHO) followed these scientific review procedures in their health risk assessment of ELF EMF in 2007, which represents one of the most comprehensive assessments on potential health effects associated with ELF EMF.

A summary of the WHO's conclusions with regard to the major outcomes they evaluated is provided in Section 3 (*Health Risk Assessment by the World Health Organization*). In addition to the WHO, a number of national and international scientific organizations have published reports or scientific statements with regard to the possible health effects of ELF EMF, which are listed in Section 4 (*Reviews and Statements by Scientific and Health Organizations*). The conclusions of these organizations are generally consistent with those of the WHO 2007 review and with the current guidance from the WHO, which states, *"... the WHO concluded that current evidence does not confirm the existence of any health consequences from exposure to low level electromagnetic fields*."[1]

Section 5 of this report then provides a systematic literature review and evaluation of relevant epidemiologic studies published from December 1, 2017 through January 31, 2022, as well as a summary of the recent *in vivo* research evaluating carcinogenesis (*Summary of Recent Research*

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[1] https://www.who.int/news-room/questions-and-answers/item/radiation-electromagnetic-fields. Accessed May 12, 2022.

Results). These recent studies, when considered in the context of previous research, do not provide sufficient evidence to alter the basic conclusion of the WHO—that the research does not confirm that electric fields or magnetic fields at the levels we encounter in our everyday environment are a cause of cancer or any other disease.

In the United States, there are no national guidelines or standards to regulate ELF EMF or to reduce public exposures. The WHO recommends adherence to the exposure limits established by the International Commission on Non-Ionizing Radiation Protection or the International Committee for Electromagnetic Safety for the prevention of acute health effects at high exposure levels, which are summarized in Section 6 (*Exposure Guidelines*).

Following their assessments of the scientific research, some scientific and health organizations recommend low-cost interventions to reduce ELF EMF exposure; the precautionary measures recommended by the WHO are summarized in Section 7 (*Precautionary Measures*).

Note that this Executive Summary provides only an outline of the material discussed in this report. Exponent's technical evaluations, analyses, conclusions, and recommendations are included in the main body of this report, which at all times is the controlling document.

1. Electric and Magnetic Fields

Both natural and man-made sources of electric and magnetic fields (EMF) surround us in our daily lives. Among natural sources of magnetic fields, the earth's geomagnetic field is perhaps the best known and has been used for compass navigation for centuries.

Man-made EMF is present wherever electricity is generated, delivered, or used, including power lines, wiring in homes and office buildings, workplace equipment, electrical appliances, power tools, and electric motors. In North America, EMF from these sources (often referred to as power-frequency EMF) changes direction and intensity, or cycles, 60 times per second; that is, it has a frequency of 60 Hertz (Hz). In Europe and other locations, 50-Hz electricity is used. Fields at these frequencies are part of the extremely low frequency (ELF) range of the electromagnetic spectrum.

ELF electricity is associated with two types of fields—electric fields and magnetic fields. Electric fields are the result of differences in voltage potentials between two points, for example, when voltages are applied to electrical conductors and equipment. The unit of measurement for electric fields is volts per meter (V/m) or kilovolts per meter (kV/m), where 1 kV/m is equal to 1,000 V/m. Most conductive objects including fences, shrubbery, and buildings easily block electric fields. Therefore, the major sources of indoor electric fields are certain appliances and other sources within homes and the workplace, while power lines represent the major source of electric fields outdoors. The intensity of electric fields diminishes with increasing distance from the source.

Magnetic fields are produced by the flow of charged particles, for example, electric currents in conductors. The strength of magnetic fields is expressed as magnetic flux density in units of gauss (G), or milligauss (mG), where 1 G is equal to 1,000 mG. (Magnetic flux density may also be expressed in units of microtesla [μT], where 1 μT is equal to 10 mG.)

The strength of the magnetic field at any point is determined by the characteristics of the source, including the amount of current flow through the source, distance from the point of measurement, and the arrangement of the conductors. As with electric fields, the intensity of magnetic fields diminishes with increasing distance from the source; however, unlike electric fields, most materials do not readily block magnetic fields. The majority of research has focused on magnetic fields because, among other reasons, conductive objects, including buildings, effectively block electric fields.

Exposure to EMF depends upon where an individual spends time and the sources he or she encounters while at these locations. Electric fields in the home range from about 0.010 kV/m away from appliances up to 0.25 kV/m near appliances (WHO, 1984). Electric fields from power lines are higher under the conductors, but are much lower as you move away from the conductors, and are almost totally blocked by walls and roofs of buildings.

Typical average household magnetic-field exposure in the United States was reported to be approximately 0.9 mG based on measurements in a representative sample of close to 1,000 households (Zaffanella, 1993). A survey of personal exposure measurements of about 1,000 persons in the United States determined that the average daily exposure for an average individual is about 1.25 mG (WHO, 1998). A similar personal measurement survey conducted among close to 400 Canadian children reported an average daily exposure of 1.21 mG (Deadman et al., 1999). In the immediate vicinity of common electrical household appliances, substantially higher magnetic fields may be experienced while the appliances are turned on. For example, at a distance of about 6 inches from microwave ovens, mixers, electric shavers, or electric can openers, the magnetic-field exposure could be 100 mG or higher (e.g., NIEHS, 2002). Typically, exposure at these levels occurs for only short periods of time.

Similar to virtually any exposure, adverse effects can be expected from exposure to very high levels of ELF EMF. If the current density or electric field induced by an extremely strong magnetic field exceeds a certain threshold, excitation of muscles and nerves is possible (ICNIRP, 2010). Also, strong electric fields can induce charges on the surface of the body that can lead to small shocks (i.e., micro shocks). These acute, shock-like effects cause no long-term damage or health consequences. Limits for the general public and workplace have been set to prevent these effects and are discussed in more detail in Section 6.

2. Scientific Review Process

The standard process for evaluating a body of research to understand the potential health implications of exposure is referred to as health risk assessment.[2]

A health risk assessment consists of several, sequential steps. The process starts with a systematic evaluation of the body of research to identify any possible risks associated with an exposure (*hazard identification*) by performing a *weight-of-evidence review*). A follow-up to hazard identification is the question, “if the exposure does cause any health risks, at what level do they occur?” (*dose-response assessment*). A risk assessment then characterizes the exposure circumstances of the situation under analysis (*exposure assessment*). Finally, using the findings from the hazard identification and dose-response assessment as a basis, along with the results of exposure assessment, a summary evaluation is provided (*risk characterization*).

2.1 Hazard identification by weight-of-evidence review

Science is more than a collection of facts; rather, it is a method of obtaining information and of reasoning to ensure that the information is accurate and correctly describes physical and biological phenomena. Many misconceptions in human reasoning occur when people casually observe and interpret their observations and experience (for example, if a person develops a headache after eating a particular food, he or she may ascribe the headache to the food). The proximity of exposures to events or conditions, however, does not guarantee a causal relationship. 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 evidence on a particular issue in a systematic and thorough manner (i.e., a weight-of-evidence review for hazard identification). 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 out from all available evidence to advocate or suppress a preconceived idea of an adverse effect. These methods include an assessment of the kind of

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[2] Some of the scientific panels that have considered EMF have described the risk assessment process in the introductory sections of their reviews or in separate publications (ICNIRP, 2002; IARC, 2006; SCENIHR, 2007; SSM, 2007; WHO, 2007; SCENIHR, 2012).

effect that can be caused by an exposure (hazard identification), as well as an assessment of the levels of exposure that can produce these effects (dose-response assessment). Thus, two steps precede arriving at a weight-of-evidence review: a systematic search to identify the relevant literature and the evaluation of each study to determine its strengths and weaknesses. Once all studies have been individually considered, the overall data are then characterized to evaluate whether they provide support for a causal relationship.

Data from several types of studies must be evaluated *together* in a weight-of-evidence review, including epidemiologic observations of human populations, experimental studies of humans, experimental studies of laboratory animals (*in vivo*), and experimental studies of isolated cells and tissues (*in vitro*). Epidemiologic and experimental studies complement one another because the inherent limitations of epidemiologic studies are addressed in experimental studies and vice versa. Similar to puzzle pieces, scientists attempt to fit the results of epidemiologic and experimental studies together to determine whether a picture of the possible relationship between exposure to a particular agent and disease can be constructed in a coherent manner.

Epidemiology is the discipline in the health sciences that studies the patterns of disease occurrence in human populations and the factors that influence these patterns. It is, therefore, part of the evidence considered for determining the causes of disease. Epidemiologic studies are observational in that they examine and analyze people in their normal daily life. Such studies are designed to quantify and evaluate the *association* between exposures (e.g., Mediterranean diet) and health outcomes (e.g., cardiovascular disease). An association is a measure of how things vary together. For example, we may find that persons with cardiovascular disease eat a diet that is lower in fat compared to people without the disease (i.e., a negative association). Or, we may find that persons with cardiovascular disease eat a diet that is higher in fat including more vegetables and fruit compared to persons without the disease (i.e., a positive association). The complexities of epidemiologic research are further illustrated by studies examining individual components of the Mediterranean diet (e.g., extra virgin olive oil) and it potential effects on cardiovascular health (Estruch et al., 2013; Lopez-Garcia et al., 2014).

Epidemiologic studies can help suggest factors that may contribute to the development of disease, but they typically cannot be used as the sole basis for drawing inferences about cause-and-effect relationships. Additional research needs to be considered. Continuing with our example from above, just because one study finds a positive association between high fat diets and cardiovascular disease, we cannot conclude that fat (or a component of fat) causes cardiovascular disease without further research. This additional research involves studies with *experimental* research designs.

In contrast to epidemiologic studies, experimental studies (including both animal studies and studies of tissues and cells) are conducted under controlled laboratory conditions. For example, in animal studies, exposure is precisely measured in the exposed group, and other factors (such as food, housing and temperature) are the same in the exposed and unexposed groups. Experimental studies are designed to test specific hypotheses under controlled conditions and are generally required to establish cause-and-effect relationships. Conversely, the results of experimental studies by themselves may not always be directly extrapolated to predict effects on human populations. It is therefore both necessary and desirable that biological responses to agents that could present a potential health threat be explored by epidemiologic methods in human populations, as well as by experimental studies in the research laboratory.

Systematic reviews with well-defined methodologies are used to support evidence-based decision making. Methods are developed to ensure the comprehensiveness and reproducibility of the selection and review processes and to minimize the potential for bias by the reviewers. A weight-of-evidence review, which is the scientific approach used by organizations such as the International Agency for Research on Cancer (IARC), WHO for health risk assessment (IARC, 2006; WHO, 2007; NTP, 2015, 2019), is essential for arriving at a valid conclusion about causality because no individual study is capable of assessing causality independently. Rather, evaluating causation is an inferential process that is based on a comprehensive assessment of all the relevant scientific research. Similarly, the strength of evidence approach, which is used for evidence-based clinical decision making, prescribes the use of methods to ensure the comprehensive and reproducible evaluation of the body of scientific evidence. Determination of the strength of the body of evidence involves assessments in three domains: quality, quantity, and consistency of the evidence (AHRQ, 2001). Quality refers to the assessment of the strengths and limitations of individual studies; quantity refers to the number of studies performed, the sample size, and the magnitude of effects observed in the studies; while consistency examines whether different approaches result in similar findings.

The following sections discuss the methods for evaluating epidemiologic and experimental research.

2.2 Evaluating epidemiologic research

As noted above, epidemiology is the science of understanding the distribution and causes of disease in human populations. The conduct of epidemiologic studies typically involves selecting and enrolling people in studies, determining their exposure status, and correlating their health events with their exposures. Scientists most commonly use two of the major analytic study designs in the field of epidemiology: case-control studies and cohort studies. A cohort study follows a pre-defined population (e.g., workers at a specific company) over time to see who develops disease. The study examines whether disease rates are different between people who were exposed to a particular agent (i.e., exposed group) and people who were not exposed (i.e., unexposed group). Cohort studies typically provide the most relevant and reliable information, but can take a great amount of time and effort to conduct, since it may take a long time for a disease to develop, and many diseases are rare, so only a few cases will occur even in a large cohort of individuals. Many cohort studies are undertaken in occupational environments because of the large populations, relatively high exposures, and the availability of records on individual workers.

Case-control studies were developed to address some of the limitations of cohort studies. A case-control study compares people who have already been diagnosed with a disease (i.e., the cases) to a similar group of people who do not have the disease (i.e., controls). The investigators measure the prevalence and extent of past exposure in both groups to assess whether the cases have a higher exposure level or more frequent exposure than the controls, or vice versa. The goal, and a major challenge, of a case-control study is to enroll a control group that represents, to the greatest extent possible, the underlying base population from which the cases arose. If this is achieved, and no bias or confounders are involved, the investigators can have some confidence that any difference found in exposure level between the two groups is not being caused by some other factor. Another challenge of case-control studies is that they are most always designed to look back in time to characterize the groups and their exposures (i.e., they are retrospective).

2.2.1 Measuring and evaluating an association

The association between a particular disease and exposure is measured quantitatively using an estimate expressed as either an relative risk (RR) or an odds ratio (OR). The general interpretation of these estimates is that a measure of association equal to 1.0 suggests that the exposure has no effect on the incidence of disease. If the estimate is greater than 1.0, the inference is that exposure increases the risk of the disease. On the other hand, if the estimate is less than 1.0, the inference is that exposure reduces the risk of the disease.

- An RR is the ratio of the rate of disease among persons who are exposed to the rate of disease among persons who are unexposed. For example, in a study of high fat diets and coronary artery disease, an RR of 2.0 can be interpreted to mean that persons with a high fat diet (i.e., exposed) when followed over time are two times more likely to develop coronary artery disease than persons with a low fat diet (i.e., unexposed).

- An OR is the ratio of the odds of exposure among persons with a disease to the odds of exposure among persons without a disease. For example, in a study of high fat diets and coronary artery disease, an OR of 2.0 would suggest that persons with coronary artery disease (i.e., cases) are two times more likely to have had a high fat diet than persons with no coronary artery disease (i.e., controls).

The RR is the better measure of a potential meaningful relationship since it directly compares the incidence of disease among exposed persons to the incidence of disease among unexposed persons and therefore more directly evaluate a causal relationship. In contrast, the OR is indirect, in that it compares exposure among persons with a disease (i.e., cases) and persons without the disease (i.e., controls). ORs are typically estimated from case-control studies, while RRs can only be measured in cohort studies. The OR in case-control studies of rare diseases are typically used to approximate the RR.

Epidemiologists typically quantify the precision of the estimated measures of association (i.e., RR, or OR) by calculating confidence intervals (CI) (i.e., the margin of statistical sampling error), usually set at 95% by convention, around the point estimates. The 95% CI represents a range of values that are expected to include the underlying effect estimate in the population 95% of the time if samples for studies were repeatedly drawn from the underlying population.

The range of the CI is also important for interpreting estimated associations. A very wide CI indicates great uncertainty about the actual value of the estimate. This is usually due to a small number of observations. The larger the number of persons being analyzed in a calculation, the smaller the likelihood that an observed association is due to a *chance* sampling error. For this reason, results based on analyses with a large sample size are more easily distinguished from chance or random variation. A narrow CI provides more certainty that the observed RR is not due to chance variation alone. But, by itself, it does not provide guidance as to the biological or health significance of this estimate.

Another way of interpreting the CI is as follows: if the 95% CI does not include 1.0, the probability of an association being due to chance (sampling variation) alone is 5% or lower and the result is considered statistically significant. As discussed elsewhere, however, statistical significance is a measure of random variability, and other factors, including study design, quality (e.g., the possibility of confounding and bias), and completeness, must be considered to determine whether or not a statistically significant association reflects a causal relationship. Often factors other than statistical significance are of greater importance in determining the credibility of a computed statistical association.

For example, a hypothetical cohort study of fat intake and coronary artery disease reported a relative risk of 1.9 (95% CI: 1.2–3.9). This is a statistically significant but weakly positive association. The data suggest that the risk of coronary artery disease is 90% higher among persons with a high fat intake compared to persons with a low fat intake, although the increase in risk could plausibly be as low as 20%, or as high as 290%, or anywhere in between, based on the 95% CI. In summary, there are three statistical considerations to consider when assessing whether a calculated RR or OR truly represents an association between the exposure and disease being studied:

1) The *probability* that the association is not attributable to chance based on a 95% CI that does not contain 1.0. The use of the CI provides more information than the statement “statistically significant.”

2) The *magnitude* of the effect estimate, which is often referred to as its strength (i.e., strong versus weak). Smaller estimates of effect are more likely to be affected by factors such as bias and confounding, as described below. Therefore, there is less certainty that a smaller estimate of effect represents a real statistical association.

3) The *precision* of the effect estimate, as measured by the range of values reported in the 95% CI. If the CI is narrow, there is less random variability.

In addition, it is necessary to evaluate whether the observed association is likely to be produced by *bias* or *confounding*. Bias refers to 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 disease. For example, if a proxy or surrogate is used to estimate exposure in place of a true exposure measurement (e.g., if a job title is used to estimate exposure to a particular agent rather than actually measuring the agent), there is the potential to introduce error into the study’s findings. A confounder is something that is related to both the disease under study and the exposure of interest such that we cannot be sure what causes the observed association—the confounder or the exposure of interest.[3] If care is not taken to evaluate the role of chance and minimize bias and confounding in the design and analysis of a study, these factors can distort the study’s findings.

2.2.2 Association versus causation

As discussed above, an association is a relationship between two events, a finding that they occur together more often than expected by chance. A reported association between a particular exposure and disease is not sufficient evidence to conclude that the exposure is a cause of the disease. Rather, an association is a finding from a particular study; evaluating causation is an

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[3] For example, a link between coffee drinking in mothers and low birth weight babies has been reported in the past. Some women who drink coffee, however, also smoke cigarettes. It was found that when the smoking habits of the mothers are taken into account, coffee drinking was not associated with low birth-weight (Kelsey et al., 1996). In this example, smoking confounded the relationship between coffee drinking and low birth weight.

inferential process that combines the totality of evidence (including epidemiologic studies that have measured associations) in a weight-of-evidence review. For example, a particular study could report that children with respiratory infections are significantly more likely to have eaten ice cream than children without respiratory infections; in other words, there is a positive association between exposure to ice cream and respiratory infections that is not likely to be due to chance. Perhaps within this study there is no association or a negative association that appears inconsistent; the association might be observed in southwestern states but not in northeastern states. Hence, it would be reckless based upon this information alone to conclude that ice cream is a cause of respiratory infections.

Linet et al. (2003) provide a thoughtful discussion on the interpretation of epidemiologic evidence. In addition to reviewing potential sources of random and systematic errors in epidemiologic research and their potential effect of interpreting the results, they discuss the importance of considering the consistency of the findings with other sources of research and with our current understanding about biological plausibility.

2.2.3 Meta- and pooled-analyses

In scientific research, the results of studies with a smaller number of subjects may be difficult to distinguish from the random variation that normally occurs in data. Meta-analysis is an analytic technique that combines the published results from a group of studies into one summary result. A pooled analysis, on the other hand, combines the raw, individual-level data from the original studies and analyzes the data from the studies altogether. These methods are valuable because they increase the number of individuals in the analysis, which allows for a more robust and stable estimate of association. Meta- and pooled analyses are also an important tool for qualitatively synthesizing the results of a large group of studies.

The disadvantage of meta- and pooled analyses is that they can convey a false sense of consistency across studies if *only* the combined estimate of effect is considered, as emphasized in standard epidemiology reference texts (e.g., Rothman and Greenland, 1998). These analyses typically combine data from studies with different study populations, methods for measuring and defining exposure, and definitions of disease. This is particularly true for analyses that combine data from case-control studies, which often use very different methods for the selection of cases and controls and exposure assessment. Therefore, in addition to the synthesis or combining of data, meta- and pooled analyses are used to understand what factors cause the results of the studies analyzed to vary, and how these factors affect the associations calculated from the data of all the studies (Rothman and Greenland, 1998). For example, Greenland et al. (2000) performed analyses to assess how excluding particular studies from the group changed the results of the analysis. Reliance on summary risk estimates from meta- or pooled analyses may be particularly problematic when there is an overall weak association, but substantial heterogeneity in results among the included studies (Linet et al., 2003). Methodological differences between studies may play a crucial role in these cases. In summary, meta- and pooled analyses are a valuable technique in epidemiology; however, in addition to calculating a summary RR, meta- and pooled analyses should analyze the factors that contribute to any heterogeneity between the studies.

2.2.4 Sub-group analyses

When interpreting the results of epidemiologic studies, epidemiologists and other scientists focus predominantly on the main results of the study (i.e., on analyses that were conducted using the entire study population, or the majority of the study population). In addition to the main analyses, researchers may also conduct sub-analyses of the data, in which subsets, or groups, of the study population are analyzed separately based on one or more shared characteristics (e.g., tumor sub-type, length of exposure duration, gender, age). The goal of sub-group analyses is to examine if and how the relationship between the exposure and outcome of interest varies across different subsets of the population, and sub-group analyses can sometimes lead to additional research questions that should be explored in future studies. However, sub-group analyses are generally considered secondary to the main analyses and should always be interpreted with caution (Fletcher, 2007; Wang et al., 2007). These analyses are not always planned before the data were collected and instead may represent *post hoc* attempts by researchers to identify any statistically significant associations in the data when none were observed in the main analyses (therefore increasing the chances of their study being published). In addition, sub-group analyses typically include fewer study participants per group compared to the main analyses; this is an issue because small sample sizes decrease the likelihood that a statistically significant finding reflects the true association between exposure and outcome and increase the likelihood that it is due to error or chance.

2.2.5 Estimation of magnetic-field exposure[4]

One of the most crucial aspects in the review of any epidemiologic study is an evaluation of how exposure was measured. A good exposure metric should measure the element that is believed to cause the disease at the appropriate time in the disease process. Estimating exposure to magnetic fields is difficult since: 1) magnetic fields occurs virtually everywhere in modern societies at varying levels; 2) exposure is often estimated retrospectively; and 3) there is currently no accepted biological mechanism for biological interactions that might influence carcinogenicity or any other disease process, so the appropriate exposure metric and timing is unknown. In the absence of substantive knowledge about a specific mechanism by which magnetic fields could affect cells, the focus on long-term exposures is based upon the standard assumption that exposures affecting the development of cancer and other diseases require repeated exposures at elevated levels, as does tobacco smoke, alcohol, sunlight, chemicals, and other agents in the environment that are known to cause disease Investigators have used magnetic-field measurements to estimate a person’s long-term average exposure (i.e., their *time-weighted average* [TWA] exposure). One method of estimating a person’s TWA exposure is to sum all magnetic-field exposures encountered during the day (e.g., while at work or school, at home, at a grocery store, shopping, etc.), weight each estimate by the number of hours in that environment, and divide that value by the total number of hours.

Exposure to magnetic fields has been quantitatively estimated in studies using a variety of methods, including:

1) Categories of exposure based on the number and thickness of power line conductors and their distance to nearby residences (wire code categories);

2) Instantaneous, spot measurements of magnetic fields in particular locations of a home;

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[4] This discussion focuses on magnetic fields since electric fields are blockedby most conductive objects, and most all studies, therefore, have focused on magnetic-field exposure.

3) Recordings of magnetic fields over 24- or 48-hour periods using either measurements in a room where a person spends most of his or her time or using a measurement device that is carried with the person; and,

4) Calculations of magnetic fields from nearby transmission lines using information on loading, height, configuration, and other data.

In general, studies that estimate long-term exposure using personal magnetic-field measurements are preferred because they evaluate exposure from all sources. Long-term personal exposure, however, also has limitations if the study subject's behavior changes over time, which will potentially affect exposure. In an analysis of children's exposure to magnetic fields in five Canadian provinces, the children wore personal exposure meters, which took single readings each minute for 48 hours to estimate the child's 48-hour average magnetic-field exposure (Armstrong et al., 2001). Since this type of measurement may be cost prohibitive, the investigators evaluated what proxy exposure measures might best predict a child's 48-hour average magnetic-field exposure. Stationary 24-hour measurements in a child's bedroom were a good predictor of 48-hour personal exposure, and spot measurements around the perimeter of the child's home were a moderately good predictor. Wire code categories reflecting the type and proximity of outside power lines, substations, and transmission lines were not found to be an accurate predictor of a child's exposure.

It is important to note that magnetic-field exposure estimates used in epidemiologic studies, while given in units of mG, are not the same as the magnetic-field values at a fixed location, such as at the edge of a transmission line right-of-way (ROW). The difference is that the exposure estimate in epidemiologic studies is intended to reflect a person's exposure to magnetic fields from all sources at all locations over a long period of time. It is evident then that brief encounters with higher magnetic-field levels (for example, walking under a distribution or transmission line, at home in front of a refrigerator or television, or at a grocery store near the freezer) would not significantly alter a person's long-term exposure to magnetic fields, as reflected in the TWA exposure, because one spends such a small fraction of time at these locations. The failure to distinguish between these two different interpretations of magnetic-field measurements is a common source of confusion (Bailey and Wagner, 2008).

2.3 Evaluating experimental studies

Experimental or laboratory studies of humans, animals, cells, and tissues complement epidemiologic studies because, while people are the species of interest, there are large variations in uncontrolled factors such as genetics, diet, and other health-related exposures in epidemiologic studies. In laboratories, variables (e.g., the intensity and duration of exposure) can be controlled to provide precise information regarding biological effects on cells or animals under defined conditions. These variables can be much better controlled or eliminated in experimental studies of animals, compared to observational studies of humans.

In vivo studies in which laboratory animals receive high exposures in a controlled environment provide an important basis for evaluating the safety of environmental, occupational, and drug exposures. These approaches are widely used by health agencies to assess risks to humans from medicines, chemicals, and physical agents (NTP, 2015, 2019).

From a public health perspective, long-term studies in which animals undergo exposure over most of their lifetime, or during their entire pregnancy, are of high importance in assessing potential risks of cancer and other adverse effects in a risk assessment. In these long-term studies, researchers examine a large number of anatomical sites to assess changes and adverse effects in body organs, cells, and tissues.

Standard protocols for long-term animal studies usually specify at least 50 animals of each sex per dose level, in each of three different dose groups. One of these dose groups is a high level termed the “maximum tolerated dose,” which is close to, but below, the level that increases mortality or produces significant morbidity. Additional dose levels are used below this maximum level. An unexposed group (i.e., the control group), is maintained under the same conditions during the same time period for comparison except for the exposure of interest. This study design permits a separate evaluation of the incidence rate, for example when studying cancer, for each tumor type in the exposed group compared to the incidence rate in the unexposed control group.

Statistical methods are used in the analysis of results to assess the role of chance in any differences in the rates between the exposed and unexposed groups, or among groups differing in the applied level of exposure. If effects are observed in a study, other studies are considered because similarity of results in different studies, laboratories, and species strengthens the evidence. Key factors in evaluating individual experimental studies include the details of the protocol; the plan for selecting animals and conducting and analyzing the study; the adequacy of the dose levels selected; the way in which the study was conducted, including adherence to good laboratory practices in animal housing and monitoring; and the evaluation of the effects on toxicity, tumors, or malformations, considering both biological and statistical issues (USEPA, 2005).

Data from long-term animal studies are instrumental in the risk assessment or weight-of-evidence process to determine whether an environmental exposure is likely to produce cancer or damage organs and tissues. The U.S. Environmental Protection Agency (EPA), for example, stated, "… the absence of tumors in well-conducted, long-term animal studies in at least two species provides reasonable assurance that an agent may not be a carcinogenic concern for humans" (USEPA, 2005, p. 2-22).

In vitro studies are designed to evaluate the way that the exposure acts on cells and tissues outside of the body (i.e., the mechanism of action). In recent years, the availability and quality of mechanistic studies to inform evaluations of carcinogenicity has increased; in response, IARC recently revised its overall evaluation process to allow for mechanistic data to be explicitly considered and integrated simultaneously along with evidence from studies of cancer in humans and in experimental animals (IARC, 2019; Samet et al., 2020). Important limitations of *in vitro* research include that the responses of cells and tissues outside the human body may not reflect the response of those same cells existing in a living system (IARC, 1992). It is difficult to extrapolate from simple cellular systems to complex, higher organisms to predict risks to health because the mechanism underlying effects observed *in vitro* may not correspond to mechanisms underlying complex processes like carcinogenesis (i.e., the progression of normal cells to cancerous cells). In addition, the results of *in vitro* studies cannot be interpreted in terms of potential human health risks unless they are performed in a well-studied and validated test system.

2.4 Evaluating causation

In order to support a cause-and-effect relationship, the cumulative data must present a logically coherent and consistent picture. Various considerations have been used to evaluate the plausibility of a cause-and-effect relationship between a particular exposure and disease. These considerations, commonly referred to as *Hill's criteria* after the British physician, Sir Austin Bradford Hill, who outlined them (Hill, 1965), typically form the foundation of causal inference (Rothman and Greenland, 1998). Although the basic tenets remain, since the publication of *Hill's criteria* in 1965, numerous revisions and updates have been published (e.g., Susser, 1991; U.S. Surgeon General, 2004). As described in Table 1, which reflects the evaluation of causation criteria outlined by the Centers for Disease Control and Prevention in 2004, *Hill's criteria*, or similar concepts, are often used as an analytic framework in the weight-of-evidence or strength-of-evidence review processes (e.g., AHRQ, 2001; ICNIRP, 2002; USEPA, 2005, 2020; NASEM, 2022). Each consideration is not met with a simple yes or no answer, nor are the considerations meant to be an inflexible set of rules; rather, they serve as guidance for weighing the evidence to reach a conclusion about cause and effect. The more firmly these considerations are met by the data, the more convincing the evidence in support of causation.

These criteria are considered only in the presence of an observed association in the epidemiologic literature. Once this has been established, the consistency, exposure-response features, and strength of this association are evaluated, in concert with the information gained from experimental studies on coherence, plausibility, and analogy. As described above, the epidemiologic data are frequently not strong enough (i.e., associations are weak, inconsistent, and do not follow a consistent pattern with dose) to draw conclusions regarding cause-and-effect solely based on epidemiologic data.

Table 1. Considerations in the evaluation of causation

Criteria	Description
Consistency	Repeated observation of an association between exposure and disease in multiple studies of adequate statistical power, in different populations, and at different times.
Strength of the association	The larger (stronger) the magnitude and statistical strength of an association is between exposure and disease, the less likely such an effect is the result of chance or unmeasured confounding.

Criteria	**Description**
Specificity	The exposure is the single cause of the disease, or one of a few causes of the disease.
Temporality	The exposure occurs prior to the onset of the disease.
Coherence, plausibility, and analogy	The association cannot violate known scientific principles and the association must be consistent with experimentally demonstrated biologic mechanisms.
Biologic gradient	The observation that the stronger or greater the exposure, the stronger or greater the effect, also known as a dose-response or exposure-response relationship.
Experiment	This occurs when observations result from situations in which natural conditions imitate experimental conditions. This criterion has also been stated as a change in disease outcome in response to a non-experimental change in exposure patterns in populations.

(Source: U.S. Surgeon General, 2004)

3. Health Risk Assessment by the World Health Organization

The WHO is a scientific organization within the United Nations system whose mandate includes providing leadership on global health matters, shaping the health research agenda, and setting norms and standards. The WHO established the International EMF Project in 1996, in response to public concerns about exposures to EMF and possible adverse health effects. The Project's membership includes 8 international organizations, 8 collaborating institutions, and over 54 national authorities. The overall purpose of the Project is to assess health and environmental effects of exposure to static (i.e., 0 Hz) and time-varying EMF in the frequency range >0 Hz to 300 Gigahertz. A key objective of the Project is to evaluate the scientific literature and make a status report on health effects to be used as the basis for a coherent international response, including the identification of important research gaps and the development of internationally-acceptable standards for EMF exposure. The WHO's weight-of-evidence review on ELF EMF was published in June 2007 as part of their Environmental Health Criteria (EHC) Programme.

The WHO used standard scientific procedures, described in Section 2, to conduct its health risk assessment. The Task Group responsible for the report's overall conclusions consisted of 21 scientists from around the world with expertise in a wide range of disciplines. The Task Group relied on the conclusions with regard to cancer from a previous weight-of-evidence review by the IARC in 2002 and mainly focused on evaluating studies on this topic published after that date.

The Task Group used specific terms to describe the strength of the evidence in support of causality. *Limited evidence* was used to describe a body of research where the findings are inconsistent or there are outstanding questions about study design or other methodological issues that preclude making strong conclusions. *Inadequate evidence* describes a body of research where it is unclear whether the data are supportive or unsupportive of causation because data are lacking or there are major quantitative or qualitative issues. The WHO also used the IARC method for categorizing exposures based on their likely carcinogenicity. Categories include (from highest to lowest risk): carcinogenic to humans, probably carcinogenic to humans, possibly carcinogenic to humans, and not classifiable as to its carcinogenicity to humans, These categories are intentionally meant to err on the side of caution, giving more weight to the possibility that the exposure is truly carcinogenic and less weight to the possibility that the exposure is not carcinogenic. The category "possibly carcinogenic to humans" was applied to magnetic fields by IARC in 2002 and re-affirmed by the WHO in 2007. It denotes exposures for which there is limited evidence of carcinogenicity in epidemiologic studies and less than sufficient (i.e., inadequate) evidence of carcinogenicity in studies of experimental animals.

The WHO Report provided the following 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 (WHO 2007a, 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 [sic]. 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 (WHO, 2007a, p. 355).*

With respect to specific health outcomes, the WHO report included the following discussions and conclusions.

3.1 Childhood leukemia

Childhood leukemia research was extensively discussed in the WHO (2007) report because the most consistently reported epidemiologic association in the area of ELF magnetic fields and health research has been reported between childhood leukemia and estimates of higher average long-term residential exposure to ELF magnetic fields. The 2002 IARC classification of ELF magnetic fields as "possibly carcinogenic to humans" was based on "limited" epidemiologic evidence from childhood leukemia epidemiologic studies. The primary support for this classification was two pooled analyses (Ahlbom et al., 2000; Greenland et al., 2000) that summarized data from previously published studies and reported an association between childhood leukemia and TWA magnetic-field exposure above 3 to 4 mG

The WHO report included a systematic evaluation of several factors that might be responsible, partially or fully, for the association observed in childhood leukemia epidemiologic studies. These factors included chance, misclassification of magnetic-field exposure, confounding from hypothesized or unknown risk factors, and control selection bias. Chance, in itself, was considered an unlikely explanation because the pooled analyses had large sample sizes. Some evidence for control selection bias in some of the previously-published studies was explored, but the evidence was not conclusive and control selection bias might not explain the entire observed association. Although a number of factors were discussed as potential confounders (e.g., socioeconomic status, residential mobility, residence type, viral contacts, environmental tobacco smoke, dietary agents, and traffic density), none of these factors was found to fully explain the observed association between childhood leukemia and estimates of long-term residential exposure to ELF magnetic fields. The possibility that some yet-to-be identified confounder is responsible for the association cannot be fully excluded, but extensive searches for such confounders have not yet identified such explanatory variables. Finally, while misclassification of magnetic-field exposure in epidemiologic studies may influence the observed association, it would likely result in an underestimate of the true association.

The WHO concluded that reconciling the epidemiologic data on childhood leukemia and the negative (i.e., no hazard or risk observed) experimental findings through innovative research is the highest priority in the field of ELF EMF research. Given that few children are expected to have long-term average magnetic-field exposures greater than 3 to 4 mG, however, the WHO stated that the public health impact of magnetic fields on childhood leukemia would be low even if the association was determined to be causal (WHO, 2007).

On childhood leukemia, the WHO concluded that

> 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 (WHO, 2007, pp. 355-356).

3.2 Adult leukemia and brain cancer

The WHO reviewed the body of research about adult leukemia and brain cancer since the IARC review in 2002. The research included three cohort studies of residential exposure, four cohort studies of occupational exposure, and eight case-control studies reporting on occupation and risk of leukemia or brain cancer (WHO, 2007). The WHO concluded:

> *In the case of adult brain cancer and leukaemia [sic], 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* (WHO, 2007, p. 307).

The WHO panel recommended updating the existing cohort studies of occupational exposure to ELF EMF and then pooling the epidemiologic data on brain cancer and adult leukemia to confirm the absence of an association.

3.3 Breast cancer

The WHO systematically reviewed many studies conducted since the publication of the IARC review in 2002 (WHO, 2007). These studies, which focused on residential magnetic-field exposure, electric blanket usage, or occupational magnetic-field exposure, did not report consistent associations between magnetic-field exposure and breast cancer. The WHO concluded that because this more recent body of research was of higher quality than previous studies and provides strong support to the conclusion of its Working Group that magnetic-field exposure does not influence the risk of breast cancer. In summary, the WHO stated:

> *[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* (WHO, 2007, p. 9).

The WHO recommended no further research with respect to breast cancer and magnetic-field exposure.

3.4 Neurodegenerative diseases

Research into the possible effect of magnetic fields on the development of neurodegenerative diseases began in 1995, and the majority of research since then has focused on Alzheimer's disease and a specific type of motor neuron disease called amyotrophic lateral sclerosis (ALS), which is also known as Lou Gehrig's disease. The inconsistency of the Alzheimer's studies prompted the National Radiological Protection Board (NRPB) of the United Kingdom to conclude that there is "*only weak evidence to suggest that it [ELF magnetic fields] could cause Alzheimer's disease*" (NRPB, 2001, p. 20). Early studies on ALS, which had no obvious biases and were well conducted, reported an association between ALS mortality and estimated occupational magnetic-field exposure. The review panels, however, were hesitant to conclude that the associations provided strong support for a causal relationship. Rather, the scientific panels felt at the time that an alternative explanation (i.e., electric shocks received at work) may be the source of the observed association. The NRPB concluded, "*In summary, the epidemiological evidence suggests that employment in electrical occupations may increase the risk of ALS, possibly, however, as a result of the increased risk of receiving an electric shock rather than from the increased exposure to electromagnetic fields*" (NRPB, 2001, p. 20).

The majority of studies reviewed by the WHO in their 2007 EHC reported statistically significant associations between occupational magnetic-field exposure and mortality from Alzheimer's disease and ALS, although the design and methods of these studies were relatively weak (e.g., disease status was based on death certificate data, exposure was based on incomplete occupational information from census data, and there was no control for confounding factors). The WHO panel also found no biological data to support an association between magnetic fields and neurodegenerative diseases and concluded that there is “inadequate” data in support of an association between magnetic fields and Alzheimer’s disease or ALS, as follows:

> 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 (WHO, 2007, p. 206).

3.5 *In vivo* experimental studies

The WHO report concluded that large-scale, long-term studies in rodents have not shown any consistent increase in any type of cancer, including leukemia, lymphoma, and mammary, brain, or skin tumors. No animal studies provide evidence that exposure to ELF EMF causes tumors .

These conclusions were based on a number of *in vivo* animal studies, including two large-scale studies that completed the National Toxicology Program protocol of testing male and female animals of two species, at three exposure concentrations, for 2 years of exposure, and performing comprehensive histopathology of multiple tissues (Boorman et al., 1999a; Boorman et al., 1999b; McCormick et al., 1999; NTP, 2011). In these studies, lifetime magnetic-field exposure did not increase leukemia or lymphoma rates, or cancers of the breast, brain, or any other site.

In addition, studies specifically designed to test cancer promotion have not found evidence that magnetic fields promote cancer. Specific exposures frequently used to initiate cancer include ionizing radiation, a chemical such as ethylnitrosourea (ENU), and another known as 7,12-dimethylbenz[a]anthracene (DMBA); ENU is known to induce brain cancers in animals exposed *in utero* (before birth), and DMBA is known to induce breast cancer in animals. For example, using mice prone to lymphoma, Babbitt et al. (2000) evaluated possible *promotional and co-promotional* effects of chronic exposure to power-frequency magnetic fields. The study used a large number of animals (2,600 mice) genetically predisposed to develop leukemia/lymphoma. To study promotion, lymphoma was first induced by ionizing radiation (gamma or Xirradiation), and then animals were exposed to either 1.4 millitesla (14,000 mG) or no magnetic field for the duration of the study. The occurrence of cancer was similar in both exposed and unexposed mice that received the same pre-treatment with ionizing radiation. This study indicated that magnetic fields do not increase the incidence of radiation-induced leukemia/lymphoma.

3.6 Experimental studies – *In vitro*

There has been no consistent or strong evidence for any explanation to explain how EMF exposure could affect biological processes in cells and tissues. In addition, as described above, such data are supplementary to epidemiologic and *in vivo* studies, and are not directly used by health agencies to assess risk to human health. For that reason, this review relies largely on reviews and conclusions of scientific panels regarding studies of mechanism.

The IARC and other scientific review panels that systematically evaluated *in vitro* studies concluded that there is no clear evidence indicating how ELF magnetic fields could adversely affect biological processes in cells (IARC, 2002; ICNIRP, 2003; NRPB, 2004). The WHO panel reviewed the *in vitro* research published since the time of the previous reviews and reached the same conclusion. The WHO noted that previous studies have not indicated a genotoxic effect of ELF magnetic fields on mammalian cells, however, a series of experiments reported DNA damage in human fibroblasts exposed intermittently to 50-Hz magnetic fields (Ivancsits et al., 2002a, 2002b; Ivancsits et al., 2003a, 2003b). These findings have not been replicated by other laboratories (e.g., Scarfi et al., 2005), and the WHO recommended continued research in this area. They also recommended research in the field of *in vitro* genotoxicity of magnetic fields combined with known DNA-damaging agents, following suggestive findings from several laboratories. As noted by the Swedish Radiation Protection Authority, the levels at which these effects were observed are much higher than the levels we are exposed to in our everyday environments and therefore are not directly relevant to questions about low-level, chronic exposure (SSI, 2007). *In vitro* studies investigating other possible mechanisms, including gene activation, cell proliferation, apoptosis, calcium signaling, intercellular communication, heat shock protein expression, and malignant transformation have produced "*inconsistent and inconclusive*" results (WHO, 2007, p. 347). A more recent and comprehensive review concluded:

> In summary, a number of in vitro studies published over the past years are relevant for the question of ELF MF exposure and neoplastic disease. However, the studies are too few and too scattered in scope and approach to provide any foundation for a conclusion on the possible neoplastic effects of ELF MF exposure. Furthermore, the studies do not provide any conclusions regarding mode of action for effects of ELF MF (SCENIHR, 2015, p. 164)

4. Reviews and Statements by Scientific and Health Organizations

A number of national and international scientific and health organizations have published reports or scientific statements regarding the possible health effects of ELF EMF since the publication of the WHO 2007 report. Although none of these documents represents a cumulative weight-of-evidence review quite as comprehensive as the WHO review published in 2007, their conclusions are nevertheless relevant.

In general, the conclusions of these other agency reviews and statements are consistent with the WHO's evaluation, as expressed on the WHO website "current evidence does not confirm the existence of any health consequences from exposure to low level electromagnetic fields. However, some gaps in knowledge about biological effects exist and need further research."[5]

The following list indicates the scientific organization and link to the online reports or statements. Although not listed below, the recent *Report on Carcinogens* from the U.S. National Toxicology Program (NTP) did not list either ELF EMF as "*Known To Be Human Carcinogens*" or "*Reasonably Anticipated To Be Human Carcinogens*" (NTP, 2021).

- **The European Health Risk Assessment Network on Electromagnetic Fields Exposure (EHFRAN)**
    - Report D-2 – Risk Analysis of Human Exposure to Electromagnetic Fields. . (EFHRAN, 2012). https://webgate.ec.europa.eu/chafea_pdb/assets/files/pdb/20081106/20081106_d1-d9_en_ps.pdf.
    - D-3 – Report on the Analysis of Risks Associated to Exposure to EMF: *in vitro* and *in vivo* (animals) studies. (EFHRAN, 2010). https://webgate.ec.europa.eu/chafea_pdb/assets/files/pdb/20081106/20081106_d1-d9_en_ps.pdf.

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[5] https://www.who.int/news-room/questions-and-answers/item/radiation-electromagnetic-fields. Last updated August 4, 2016. Accessed May 12, 2022.

- **The Health Council of Netherlands (HCN)**
  - Advisory – BioInitiative Report. (HCN, 2008a) https://www.healthcouncil.nl/documents/advisory-reports/2008/09/02/bioinitiative.
  - High Voltage Power Lines. (HCN, 2008b) https://www.healthcouncil.nl/documents/advisory-reports/2008/02/21/high-voltage-power-lines.
  - Electromagnetic Fields: Annual Update 2008. (HCN, 2009a). https://www.healthcouncil.nl/documents/advisory-reports/2009/03/19/electromagnetic-fields-annual-update-2008.
  - Advisory Letter: Power Lines and Alzheimer's Disease. (HCN, 2009b). https://www.healthcouncil.nl/documents/advisory-reports/2009/03/30/power-lines-and-alzheimers-disease.
- **The Health Protection Agency (HPA)**
  - Power Frequency Electromagnetic Fields, Melatonin and the Risk of Breast Cancer. Report of an independent Advisory Group on Non-ionising Radiation (AGNIR, 2006). https://www.gov.uk/government/publications/power-frequency-electromagnetic-fields-emfs-melatonin-and-risk-of-breast-cancer.
- **The International Commission on Non-Ionizing Radiation Protection (ICNIRP)**
  - ICNIRP Guideline for Limiting Exposure to Time-Varying Electric and Magnetic Fields (1 Hz – 100 kHz). (ICNIRP, 2010). http://www.icnirp.org/cms/upload/publications/ICNIRPLFgdl.pdf.
- **The Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR)**
  - Possible Effects of Electromagnetic Fields (EMF) on Human Health. (SCENIHR, 2007). http://ec.europa.eu/health/ph_risk/committees/04_scenihr/docs/scenihr_o_007.pdf.
  - Health Effects of Exposure to EMF. (SCENIHR, 2009). http://ec.europa.eu/health/ph_risk/committees/04_scenihr/docs/scenihr_o_022.pdf
  - Opinion on Potential Health Effects of Exposure to Electromagnetic Fields (SCENIHR, 2015). http://ec.europa.eu/health/scientific_committees/emerging/docs/scenihr_o_041.pdf

- **The Swedish Radiation Protection Authority (SSI)**
    - Recent Research on EMF and Health Risks. Fourth Annual Report from SSI's Independent Expert Group on Electromagnetic Fields, 2006. SSI Rapport 2007:04 (SSI, 2007). https://www.stralsakerhetsmyndigheten.se/contentassets/54f003dfe0ec4a24a9b212963841983f/200704-recent-research-on-emf-and-health-risks.-fourth-annual-report-from-ssis-independent-expert-group-on-electromagnetic-fields-2006.
    - Recent Research on EMF and Health Risks. Fifth Annual Report from SSI's Independent Expert Group on Electromagnetic Fields, 2007. SSI Rapport 2008:02 (SSI, 2008). https://www.stralsakerhetsmyndigheten.se/en/publications/reports/radiation-protection/2008/200812/
- **The Swedish Radiation Safety Authority (SSM)**
    - Recent Research on EMF and Health Risks: Sixth annual report from SSM's independent Expert Group on Electromagnetic Fields 2009. (SSM, 2009). http://www.stralsakerhetsmyndigheten.se/Global/Publikationer/Rapport/Stralskydd/2009/SSM-Rapport-2009-36.pdf.
    - Recent Research on EMF and Health Risks: Seventh annual report from SSMs independent Expert Group on Electromagnetic Fields 2010. SSM Rapport 2010:44. (SSM, 2010). http://www.stralsakerhetsmyndigheten.se/Global/Publikationer/Rapport/Stralskydd/2010/SSM-Rapport-2010-44.pdf.
    - Recent Research on EMF and Health Risk. Eighth Report from SSM:s Scientific Council on Electromagnetic Fields. (SSM, 2013). http://www.stralsakerhetsmyndigheten.se/Publikationer/Rapport/Stralskydd/2013/201319/
    - Recent Research on EMF and Health Risk. Ninth report from SSM's Scientific Council on Electromagnetic Fields. Research 2014:16. (SSM, 2014). https://www.stralsakerhetsmyndigheten.se/contentassets/08b2f497b3ad48cf9e29a1d0008e7d82/201416-recent-research-on-emf-and-health-risk-ninth-report-from-ssms-scientific-council-on-electromagnetic-fields-2014.
    - Recent Research on EMF and Health Risk - Tenth report from SSM's Scientific Council on Electromagnetic Fields. Research 2015:19. (SSM, 2015). https://www.stralsakerhetsmyndigheten.se/contentassets/ee7b28e0fee04e80bcaf84c24663a004/201519-recent-research-on-emf-and-health-risk---tenth-report-from-ssms-scientific-council-on-electromagnetic-fields-2015.
    - Recent Research on EMF and Health Risk - Eleventh report from SSM's Scientific Council on Electromagnetic Fields, 2016. Including Thirteen years of electromagnetic field research monitored by SSM's Scientific Council on EMF and health: How has the evidence changed over time? (SSM, 2016).

https://www.stralsakerhetsmyndigheten.se/contentassets/98d67d9e3301450da4b8d2e0f6107313/201615-recent-research-on-emf-and-health-risk-eleventh-report-from-ssms-scientific-council-on-electromagnetic-fields-2016.

  - Recent Research on EMF and Health Risk - Twelfth report from SSM's Scientific Council on Electromagnetic Fields, 2017. Research 2018:09. (SSM, 2018). https://www.stralsakerhetsmyndigheten.se/contentassets/f34de8333acd4ac2b22a9b072d9b33f9/201809-recent-research-on-emf-and-health-risk.

  - Recent Research on EMF and Health Risk - Thirteenth report from SSM's Scientific Council on Electromagnetic Fields, 2018. Research 2019:08. (SSM, 2019). https://www.stralsakerhetsmyndigheten.se/contentassets/ea182ee131d049f1b3b1140dd0fbc0f8/201908-recent-research-on-emf-and-health-risk-thirteenth-report-from-ssms-scientific-council-on-electromagnetic-fields-2018.pdf.

  - Recent Research on EMF and Health Risk - Fourteenth report from SSM's Scientific Council on Electromagnetic Fields, 2019. Research 2020:04. (SSM, 2020). https://www.stralsakerhetsmyndigheten.se/contentassets/47542ee6308b4c76b1d25ae0adceca15/2020-04-recent-research-on-emf-and-health-risk---fourteenth-report-from-ssms-scientific-council-on-electromagnetic-fields-2019.pdf

  - Recent Research on EMF and Health Risk. Fifteenth report from SSM's Scientific Council on Electromagnetic Fields, 2020. (SSM, 2021). https://www.stralsakerhetsmyndigheten.se/contentassets/fce87121bd5e47ca95ad16d93d03f638/202108-recent-research-on-emf-and-health-risk.pdf.

- **The New Zealand Ministry of Health (NZMH)**

  - Interagency Committee on the Health Effects of Non-ionising Fields: Report to Ministers 2015. (NZMH, 2015). http://www.health.govt.nz/system/files/documents/publications/interagency-committee-on-health-effects-on-non-ionising-fields-may15.pdf.

  - Interagency Committee on the Health Effects of Non-ionising Fields: Report to Ministers 2018. (NZMH, 2018). https://www.health.govt.nz/publication/interagency-committee-health-effects-non-ionising-fields-report-ministers-2018

5. Summary of Recent Research Results

Scientific research investigating various aspects of biological interactions and potential health effects associated with ELF EMF has continued since the completion of the WHO EHC on ELF fields. This section identifies and describes epidemiologic studies related to ELF EMF and health published between December 1, 2017, and January 31, 2022, and provides a summary of the conclusions of recent *in vivo* studies of carcinogenesis. The purpose of this section is to evaluate whether the findings of these recent studies alter the conclusions published by the WHO in their 2007 report, as described in Section 3, and more recent reviews by scientific and health organizations, as summarized in Section 4. The research is also evaluated with the context of a previous Exponent report that summarized the literature through December 2017 (Exponent, 2017). Exponent (2017) concluded that the results of the reviewed research did not provide sufficient evidence to alter the basic conclusion of the WHO 2007 review.

A structured literature search was conducted using PubMed, a search engine provided by the National Library of Medicine and the National Institutes of Health that includes over 33 million up-to-date citations from MEDLINE and other life science journals for biomedical articles (http://www.pubmed.gov). A well-defined search strategy was used to identify English language literature indexed between December 1, 2017 and January 31, 2022.[6] All fields (e.g., title, abstract, keywords) were searched with various search strings that referenced the exposure and disease of interest.[7] A researcher with experience in this area reviewed the titles and abstracts of these publications for inclusion in this evaluation. The following specific inclusion criteria were applied:

1. **Outcome**. Epidemiologic studies evaluated cancer; reproductive or developmental effects; neurodegenerative diseases; or cardiovascular disease, while *in vivo* studies evaluated

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[6] Since there is sometimes a delay between the publication date of a study and the date it is indexed in PubMed, it is possible that some studies not yet indexed, but published prior to January 31, 2022, are not included in this update.

[7] EMF OR magnetic fields OR electric fields OR electromagnetic OR power frequency OR transmission line AND cancer (cancer OR leukemia OR lymphoma OR carcinogenesis) OR neurodegenerative disease (neurodegenerative disease OR Alzheimer's disease OR amyotrophic lateral sclerosis OR Lou Gehrig's disease) OR cardiovascular effects (cardiovascular OR heart rate) OR reproductive outcomes (miscarriage OR reproduction OR developmental effects).

carcinogenicity. Research on other outcomes was not included (e.g., psychological effects, behavioral effects, hypersensitivity).

2. **Exposure**. Studies evaluated ELF EMF at a frequency of 50 or 60-Hz.
3. **Exposure assessment methods**. Studies evaluated exposure beyond self-report of an activity or occupation, and estimated exposure through various methods including calculated EMF levels using distance from power lines, measured TWA exposure, and average exposure estimated from job-exposure matrices (JEM).
4. **Study design**. Study design included epidemiologic studies, meta-analyses, pooled analyses, human experimental studies, and *in vivo* studies of carcinogenicity. The review relies on the conclusions of the WHO with regard to *in vivo* studies in the areas of reproduction, development, neurology, and cardiology. Further, this report relies on the conclusions of the WHO report (as described in Section 3) regarding mechanistic data from *in vitro* studies since this field of study is less informative to the risk assessment process than are epidemiology and *in vivo* studies (IARC, 2002).
5. **Peer-review**. The study must have been peer-reviewed and published. Therefore, no conference proceedings, abstracts, or non-peer reviewed on-line materials were included.

Epidemiologic studies are evaluated below first by outcome (childhood cancer; adult cancer; reproductive or developmental effects; neurodegenerative disease; and cardiovascular effects), followed by an evaluation of *in vivo* research on carcinogenesis.

5.1 Childhood leukemia

Since the WHO published their 2007 report, childhood leukemia continues to be a main focus of ELF EMF epidemiologic research. Kheifets et al. (2010a) provided an update to the analyses conducted by Ahlbom et al. (2000) and Greenland et al. (2000) by reporting the results of a pooled analysis of seven case-control studies of childhood leukemia and ELF EMF published between 2000 and 2010. Although the authors included a large number of cases (n = 10,865) in this analysis, only a small number of cases had measured fields (n = 23) or calculated fields (n = 3) in the highest exposure category (≥ 3 mG). A moderate and statistically not significant association was reported for the highest exposure category, which was weaker than the association reported in the previous pooled analyses (Ahlbom et al., 2000; Greenland et al., 2000). Additional meta-analyses and pooled analyses conducted during this time period, which were summarized in Exponent (2017), did not provide any strong evidence against the conclusions of the WHO 2007 review (e.g., Zhao et al., 2014a; Su et al., 2016; Zhang et al., 2016a).

As summarized Exponent (2017), several large case-control studies from France (Sermage-Faure et al., 2013), Denmark (Pedersen et al., 2014a; Pedersen et al., 2014b; Pedersen et al., 2015), the United Kingdom (Bunch et al., 2014; Bunch et al., 2015, 2016), and the United States (Kheifets et al., 2015; Vergara et al., 2015a; Crespi et al., 2016; Kheifets et al., 2017) published since the WHO 2007 report assessed the risk of childhood leukemia in relation to residential proximity to high-voltage power lines. None of these studies reported consistent overall associations between childhood leukemia development and residential distance to high-voltage power lines. The largest of these studies (Bunch et al., 2014) was an update of an earlier study in the United Kingdom (Draper et al., 2005) and included over 53,000 childhood cancer cases diagnosed between 1962 and 2008 and over 66,000 healthy children as controls. Overall, the authors reported no association between childhood leukemia development and residential proximity to power lines with any of the voltage categories. The statistical association reported in the earlier study (Draper et al., 2005) was no longer apparent in the updated analysis (Bunch et al., 2014).

Recent studies on childhood leukemia (December 1, 2017 through January 31, 2022)

California Power Line Study

Several recent studies (Amoon et al., 2018a; Amoon et al., 2019; Crespi et al., 2019; Amoon et al., 2020) used the same California study population as Crespi et al. (2016) and Kheifets et al. (2017). Amoon et al. (2018a) assessed the potential impact of residential mobility of the study subjects (i.e., moving residences between birth and diagnosis) on the associations reported in Crespi et al. (2016). The authors reported that changing residences was not associated with either calculated fields or proximity to ≥ 200-kV power lines and concluded that "[m]obility appears to be an unlikely explanation for the associations observed between power lines [*sic*] exposure and childhood leukemia" in the previous study (Amoon et al., 2018a, p. 459).

In further analyses, Amoon et al. (2019, 2020) assessed the role of residential mobility and dwelling type in estimating the potential effect of magnetic-field exposure on childhood leukemia risk. Amoon et al. (2019) reported that residential mobility had some impact on the association between magnetic-field exposure and childhood leukemia, but concluded that confounding by residential mobility is “unlikely to be the primary driving force behind previously observed largely consistent, but unexplained associations” (Amoon et al., 2019, p. 7). Amoon et al. (2020) reported that while Black race (adjusted odds ratio [aOR]: 1.64; 95% CI:1.03–2.59) and low socioeconomic status (aOR: 1.25; 95 CI:1.07–1.45]) were associated with dwelling type (i.e. having an apartment or mobile home as opposed to a duplex or single-family home), dwelling type was not associated with childhood leukemia, and thus did not appear to be a confounder in the relationship between magnetic-field exposure and childhood leukemia risk in this study. The authors reported potential differences in the strength of the association between childhood leukemia and magnetic-field exposure by dwelling type and recommended additional research in this area.

Crespi et al. (2019) investigated the separate and combined relationship between distance from high-voltage power lines and calculated magnetic-field exposure and childhood leukemia risk. The authors reported that neither residential proximity to high-voltage power lines (< 50 meters, ≥ 200 kilovolts [kV]) nor calculated magnetic fields (≥ 0.4 µT [≥ 4 mG]) alone were associated with childhood leukemia; however, an association was observed for study subjects with both residential proximity to high-voltage power lines and high calculated magnetic fields (OR: 4.06; 95% CI: 1.16, 14.3). No associations were observed with low-voltage power lines. The authors considered their study as “hypothesis generating” and noted that the observed associations could be spurious findings due to small sample sizes or confounding. The authors concluded that their findings “argue against magnetic fields as a sole explanation” for an association between distance and childhood leukemia and “in favor of some other explanation” linked to the power lines (Crespi et al., 2019, p. 535).

Cohort studies[8]

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[8] See Section 3.2 *Evaluating epidemiologic research* for a description of the epidemiologic study designs.

Auger et al. (2019a) examined the relationship between residential proximity to high-voltage transmission lines and transformer stations during pregnancy of the mother and risk of childhood cancer in the offspring in a cohort of 784,000 children born in Québec and followed for one decade after birth. No statistically significant associations were reported between distance to high-voltage power lines or transformer stations and any cancer outcomes, including hematopoietic cancer and solid tumors (Auger et al., 2019a). The authors concluded that their results "*suggest an absence of a causal link between [EMF] from high voltage power sources and the risk of cancer in children*" (Auger et al., 2019a, p. 6).

Case control studies

Kyriakopoulou et al. (2018) conducted a case-control study to examine the potential relationship between parental occupational exposures and childhood acute leukemia. No statistically significant associations were observed between parental occupational exposure to "*electromagnetic-field*" (i.e., as this paper refers to ELF magnetic fields) and risk of childhood acute leukemia for any of the investigated exposure periods (i.e., 1 year before conception, during pregnancy, during breastfeeding, and from birth until diagnosis). The size of the group exposed to magnetic fields was very small (6% of workers) compared to the other three exposure groups, which limits the statistical precision and interpretations of the data. An additional limitation is the assignment of exposure based on job title, which does not account for differences in exposure across individuals with the same occupation.

Núñez-Enríquez et al. (2020) conducted a case-control study to assess the relationship between residential magnetic-field exposure and B-lineage acute lymphoblastic leukemia (B-ALL) in Mexico City, Mexico. The study included children less than 16 years of age (290 cases and 407 controls). Exposure to magnetic-field exposure was assessed using 24-hour measurements in the participants' bedrooms. The authors reported statistically significant associations between B-ALL and 24-hour magnetic-field exposures ≥ 0.4 µT (4 mG) (aOR: 1.87; 95% CI:1.04-3.35) and ≥ 0.6 µT (6 mG) (aOR: 2.32; 95% CI:1.10-4.93); however, non-statistically significant associations were reported for 24-hour magnetic field exposures ≥ 0.2 µT [2 mG], ≥ 0.3 µT [3 mG], and ≥ 0.5 µT [5 mG]. The authors concluded that *"to date, a clear mechanism through which exposure to ELF- MFs [magnetic fields] may be associated with leukemia has not been* *established. Therefore, it is possible that other factors related to ELF - MF exposure, which we could not identify in the present study, may be relatively more relevant as risk factors for childhood leukemia development"* (Núñez-Enríquez et al., 2021, p. 9). Reliance on 24-hour measurements, the large proportion of participants with higher magnetic-field exposures (14% of cases and 11% of controls had 24-hour exposures ≥ 0.3 µT [3 mG]), and the ability to analyze the most common childhood leukemia subtype (B-ALL) separately are among the study's strengths. The statistically significantly higher frequency of infections during the first year of life among cases compared to controls(OR: 2.22 [95% CI:1.14-4.33]) , may be indicative of potential confounding. The hospital-based selection of controls may be a source of selection bias, if the catchment areas of the hospitals used to recruit controls were different than those of the hospitals where the leukemia cases were treated and recruited. Participation rate was also lower among cases than among controls, representing another potential source of selection bias.

Meta-analyses and pooled analyses

Amoon et al. (2018b) conducted a meta-analysis of epidemiologic studies of residential distance to power lines and childhood leukemia. The authors pooled the data from 11 studies with record-based assessments of residential distance from high-voltage power lines from 10 countries (Australia, Brazil, Denmark, France, Italy, Norway, Sweden, Switzerland, the United Kingdom, and the United States); this included the previously mentioned studies by Pedersen et al. (2014a), Sermage-Faure et al. (2013), Bunch et al. (2014), and Crespi et al. (2016). In total, 29,049 cases and 68,231 controls were included in the analyses. The authors reported no statistically significant associations when proximity to transmission lines with any voltage was investigated; the observed associations were slightly stronger for leukemia case diagnoses before 5 years of age and in study periods prior to 1980. Adjustment for various potential confounders (e.g., socioeconomic status, dwelling type, residential mobility) had little effect on the estimated the associations.

Swanson et al. (2019) examined 41 studies to assess the trends in childhood leukemia risk over time. The authors reported a statistically non-significant decline in risk from the mid-1990s until the present, which they stated was "*unlikely to be solely explained by improving study quality but may be due to chance*" (Swanson et al., 2019, p. 470). The authors concluded, however, that the current body of literature on EMF "*argue against health effects of MFs [magnetic fields] at these exposure levels*" (Swanson et al., 2019, p. 485).

Talibov et al. (2019) conducted a pooled analysis of 11 case-control studies examining the relationship between parental occupational exposure to ELF magnetic fields and childhood leukemia. No statistically significant association was found for paternal or maternal exposure by leukemia sub-type or overall, and no association was observed when additional exposure categories were used. The authors concluded that their study "*suggests that parental ELF-EMF exposure plays no relevant role in the aetiology of childhood leukemia*" (Talibov et al., 2019, p. 752).

Amoon et al. (2022) conducted a pooled analysis of and included original data from epidemiologic studies of residential exposure to magnetic fields and childhood leukemia published after the 2010 pooled analysis (Kheifets et al., 2010). The study compared the exposures of 24,994 children with leukemia to those of 30,769 controls without leukemia to measured or calculated magnetic fields at their residences in California, Denmark, Italy and the United Kingdom (Amoon et al., 2022). The exposures of these two groups to magnetic fields were found to not significantly differ, so the authors reported *"[u]nlike previous pooled analyses, we found no increased risk of leukemia [above 0.4 µT (i.e., 4 mG)]*" and *"[i]n conclusion, our results do not show the risk increase observed in previous pooled analysis and, over time, show a decrease in effect to no association between MF and childhood leukemia*" (Amoon et al., 2022, pp. 1, 6).

Investigators from Korea conducted a systematic review and meta-analysis of exposure to ELF magnetic fields and childhood cancer (Seomun et al., 2021). The authors included 30 studies in their meta-analyses and reported that *"[c]hildren exposed to 0.2-, 0.3-, and 0.4-µT [i.e., 2, 3, and 4 mG] ELF-MFs [magnetic fields] had a 1.26 (95% confidence interval [CI] 1.06–1.49), 1.22 (95% CI 0.93–1.61), and 1.72 (95% CI 1.25–2.35) times higher odds of childhood leukemia*" (Seomun et al., 2021, p.1). The authors did not specifically evaluate the change in association between ELF magnetic fields and childhood leukemia over time, and the overall results were likely influenced by the larger number of earlier studies.

Summary of recent research on childhood leukemia

The results of recent studies do not change the WHO classification of the epidemiologic data on childhood leukemia as limited. While many of the recently published large and methodologically advanced studies showed no statistically significant associations between estimates of magnetic-field exposure from power lines, the association between childhood leukemia and magnetic fields observed in some earlier studies remains unexplained. This is the assessment of the most recent review released in 2015 by SCENIHR, which concluded that the epidemiologic data on childhood leukemia and EMF exposure reviewed for the report "*are consistent with earlier findings of an increased risk of childhood leukaemia with estimated daily average exposures above 0.3 to 0.4 µT [i.e., 3 to 4 mG]*" and noted that "*no mechanisms have been identified and no support is existing [sic] from experimental studies that could explain these findings, which, together with shortcomings of the epidemiological studies prevent a causal interpretation*" (SCENIHR, 2015, p. 164). A similar conclusion was reached by SSM in their most recent review of the research, in which they concluded, "*[r]egarding the exposure to ELF magnetic fields and the development of childhood leukaemia, associations have been observed, but a causal relationship has not been established*" (SSM, 2021, p. 6).

5.2 Childhood brain cancer

Compared to the research on magnetic fields and childhood leukemia, there have been fewer published studies of childhood brain cancer. In 2010, in response to WHO research recommendations, both a meta-analysis (Mezei et al., 2008) and a pooled analysis (Kheifets et al., 2010b) was conducted for childhood brain cancer to provide comparable data to the childhood leukemia pooled analyses. Mezei et al. (2008) reported no overall association but observed a statistically non-significant weak association with calculated or measured magnetic fields above 3 to 4 mG based on a sub-analysis of five studies. Kheifets et al. (2010b)) included data from 10 previously published epidemiologic studies and included over 8,000 childhood brain cancer cases. None of the analyses showed statistically significant increases, and while some categories of high exposure had an OR > 1.0, the overall patterns were not consistent with an association and no dose-response trends were apparent. The authors concluded that their results provide little evidence for an association between magnetic fields and childhood brain cancer.

Some of the large epidemiologic studies of childhood leukemia summarized in Exponent (2017) also examined childhood brain cancer and its potential association with measures of exposure to EMF (e.g., Bunch et al., 2014, 2015, 2016; Pedersen et al., 2015; Crespi et al., 2016). None of these studies reported a consistent association between any of the investigated magnetic-field exposure metrics and brain cancer development among children.

Recent studies on childhood brain cancer (December 1, 2017 through January 31, 2022)

Cohort studies

The previously discussed study on childhood leukemia by Auger et al. (2019) also investigated the association between exposure to EMF during pregnancy and the occurrence of central nervous system (CNS) tumors in the offspring. The authors reported a statistically non-significant association between a residential distance of 80 meters from a transformer station and CNS tumors (OR: 1.15; 95% CI 0.94, 1.41). When the analysis was stratified by gender, the authors reported an association for males only. No associations were observed with distance to transmission lines. The authors concluded that "*[r]esidential proximity to transformer stations is associated with a borderline risk of childhood cancer, but the absence of an association with transmission lines suggests no causal link*" (Auger et al., 2019, p. 1).

Meta-analyses and pooled analyses

Su et al. (2018) conducted a meta-analysis of epidemiologic studies that investigated the association between parental occupational exposure to ELF magnetic fields and childhood CNS tumors. The authors included a total of 22 case-control and cohort studies published as of December 2017 in their analysis. For CNS tumors, they reported a weak statistically significant association (OR: 1.16; 95% CI: 1.06, 1.26) for maternal exposure to ELF magnetic fields based on a subset of eight studies, but no statistically significant associations for paternal exposure. The authors reported no association for neuroblastoma with either maternal or paternal exposure to ELF magnetic fields. The authors assessed the impact of study quality on the observed associations and noted inconsistent effects for maternal and paternal exposures. When based on higher quality studies, the authors noted that the observed associations were stronger for maternal exposure (OR: 1.14; 95% CI: 1.05, 1.23), but weaker for paternal exposure (OR: 1.05; 95% CI: 0.98, 1.13). It is noteworthy that associations were statistically significant only when studies using non-quantitative exposure methods (i.e., relying on job titles only) were pooled, but no associations were reported based on studies with a quantitative exposure assessment. The authors also reported evidence for publication bias. While most of the included studies investigated cancer among children, some of the studies also included persons with tumors diagnosed up to 30 years of age, which is an additional limitation of the analysis.

The meta-analysis of Seomun et al. (2021) described above in the section on childhood leukemia also included studies of childhood brain cancer. No statistically significant associations were reported; the OR was 0.95 (95% CI: 0.59-1.56) for magnetic-field exposure > 0.2 µT (> 2 mG), and 1.25 (95% CI: 0.45-3.45) for magnetic-field exposure > 0.4 µT (> 4 mG).

Summary of research on childhood brain cancer

The literature on childhood brain cancer is not as robust as the research on magnetic fields and childhood leukemia. Nevertheless, the results of recent studies do not alter the classification of the epidemiologic data as inadequate, as they did not report any consistent or convincing evidence for an association. This is in line with the 2015 SCENIHR review, which concluded that "*no association has been observed for the risk of childhood brain tumours*" (SCENIHR, 2015, p. 158).

5.3 Adult leukemia and lymphoma

Research on adult leukemia and ELF magnetic fields, most of which is related to occupational exposure, has generally been inconsistent—some studies report a positive association between measures of ELF magnetic fields and leukemia, while other studies show no association. No pattern has been identified whereby studies of higher quality or design are more likely to produce positive or negative associations. Studies reviewed in Exponent (2017) did not provide evidence to change the WHO 2007 review's conclusion that the epidemiologic evidence for adult leukemia is inadequate.

Recent studies on adult leukemia and lymphoma (December 1, 2017 through January 31. 2022)

Cohort studies

Huss et al. (2018) conducted a census-based retrospective cohort study examining exposure to ELF magnetic fields and death from several types of hematopoietic malignancies within the Swiss National Cohort. The authors included a total of 3.1 million economically active individuals between 30 and 65 years of age (for men) or 30 and 62 years of age (for women) who participated in the 1990 or 2000 census, or both, in Switzerland. Mortality from different malignant neoplasms of the lymphoid and hematopoietic tissue (i.e., various types of acute and chronic leukemias and lymphomas) was evaluated from 1990 to 2008. Occupational exposure to ELF magnetic fields was assessed based on the study subjects' job title as reported at the time of the census and a JEM developed for ELF magnetic fields. In addition, they assessed potential confounding by other occupational exposures, including solvents, pesticides, herbicides, metals, and electric shocks by applying corresponding JEMs to the study subjects' job titles and adjusting for the exposures in the main analyses.

None of the hematopoietic cancer types included in the main analyses was statistically associated with either exposure corresponding to a median intensity of 0.19 µT (1.9 mG) or a higher exposure of 0.52 µT (5.2 mG) in the fully-adjusted models with the exception of myeloid leukemia (hazard ratio [HR]: 1.31; 95% CI:1.02-1.67) and acute myeloid leukemia [HR: 1.26; 95% CI:0.83-1.70) among men who were ever highly exposed. Adjustment for the other occupational exposures had a very small effect on the risk estimates. The authors also reported statistically significant associations for myeloid leukemia and acute myeloid leukemia among men who were ever highly exposed at the time of both censuses and additionally during their vocational training (n = 5 cases each). As noted, both estimates were based on a very small number of cases. Lung cancer mortality, included as a negative control outcome, showed statistically significant associations and a clear exposure-response pattern with exposure to ELF magnetic fields. This finding clearly indicates that confounding by smoking, which is a well-established cause of both lung cancer and leukemias/lymphomas, remains a major weakness of the study, and may explain the association reported in some of the sub-analyses. The authors concluded that their analysis "*provided no convincing evidence for an increased risk of death* *from hematopoietic cancers in workers occupationally exposed to ELF magnetic fields*" (Huss et al., 2018a, p. 467).

Khan et al. (2021) reported results on the development of hematological neoplasms, including lymphoma and leukemia, and brain cancer cases in a cohort study of over 250,000 individuals who lived in residential buildings with indoor transformer stations in Finland. Exposure to magnetic fields was assessed based on the location of the participants' apartment in relation to the location of the transformer station in the building; those participants who lived for at least 1 month in an apartment located directly above a transformer room or that shared a wall with a transformer room were considered exposed (n = 9,636 exposed individuals). Based on very small number of cases (n = 4), a statistically significant association was reported for acute lymphocytic leukemia (HR: 2.86; 95% CI: 1.00–8.15); this association was observed to increase with duration of exposure (HR: 3.61; 95% CI: 1.05–12.4, for exposure ≥ 3 years). No associations were reported for other leukemia subtypes or for lymphoma or multiple myeloma, and the risk level for these diseases decreased with increasing duration of exposure. The study's prospective design minimized potential for selection bias (no contact was required with the study subject), and a previously validated exposure classification system (Okokon et al., 2014) are among its strengths. Limitations of the study include the low number of cases and the exposure assessment method, which did not account for personal behavior and time spent in the apartment that may influence personal exposure or potential confounding exposures.

Meta-analyses and pooled analyses

The cohort study by Huss et al. (2018a) also conducted a meta-analysis of 28 epidemiologic studies of occupational exposure to ELF magnetic fields and acute myeloid leukemia published until September 2017. The authors reported a weak overall association, with a summary RR (sRR) of 1.21 (95% CI: 1.08, 1.37).

Odutola et al. (2021) conducted a systematic review and meta-analysis of various occupational exposures and follicular lymphoma, a common non-Hodgkin lymphoma subtype. The authors identified only two studies that specifically investigated occupational ELF magnetic-field exposure (Koeman et al., 2014; Huss et al., 2018). The authors concluded that they found "*no* *consistent evidence*" of a relationship between follicular lymphoma and ELF magnetic-field exposure (Odutola et al., 2021, p. 17).

Summary of research on adult leukemia and lymphoma

Recent studies did not provide substantial evidence for an association between EMF and leukemia overall, leukemia sub-types, or lymphoma in adults. While some scientific uncertainty remains on a potential relationship between adult lymphohematopoietic malignancies and magnetic-field exposure because of continued deficiencies in study methods, the previous conclusion of the WHO that the evidence is inadequate for adult leukemia remains appropriate. (EFHRAN, 2012; SCENIHR, 2015). The most recent SCENIHR report states that, overall, studies on "*adult cancers show no consistent associations*" (SCENIHR, 2015, p. 158).

5.4 Adult brain cancer

Brain cancer was studied along with leukemia in many of the occupational studies of ELF magnetic fields. The findings were inconsistent, and there was no pattern of stronger findings in studies with more advanced methods, although a small association could not be ruled out. The WHO subsequently classified the epidemiologic data on adult brain cancer as inadequate. Overall, epidemiologic studies of ELF magnetic fields and adult brain cancer published since the WHO 2007 report, including those that were reviewed in Exponent (2017), predominantly support no association with brain cancer in adults, but remain limited due to the exposure assessment methods and insufficient data available on specific brain cancer subtypes.

Recent studies on adult brain cancer (December 1, 2017 through January 31, 2022)

Cohort studies

Khan et al. (2021), previously described in the section on adult leukemia and lymphoma, also reported results on newly diagnosed brain cancer cases. The authors reported no association between magnetic-field exposure and meningioma based on residential location, and a non-statistically significant association with glioma. No association was reported between brain tumors and duration of residence near transformers. As discussed above, the study's limitations include the low number of cases and the lack of personal exposure data or information on potential confounding exposures.

Case-control studies

Carlberg et al. (2018, 2020) published the results of several case-control epidemiologic studies of occupational exposure to ELF EMF and brain cancer. The authors in Carlberg et al. (2018, 2020) used a similar approach and methods as in a previous study (Carlberg et al., 2017) and relied on data from previously published case-control studies in Sweden (Hardell et al., 2006; Hardell et al., 2013). Cases and controls were ascertained from the Swedish Population Registry during the periods of 1997 to 2003 and 2007 to 2009, and occupational exposure to ELF magnetic fields was assessed from self-reported questionnaires on lifetime occupational history and a previously developed JEM (Turner et al., 2014). Carlberg et al. (2018) included 1,592 meningioma cases and 3,485 controls and reported no trend or association between meningioma development and any of the investigated metrics of occupational exposure to ELF magnetic fields (i.e., average occupational exposure, highest exposed job, or cumulative exposure) regardless of the time windows investigated (i.e., exposure during 1 to 14 years prior to diagnosis, or exposure more than 15 years prior to diagnosis). The authors concluded that "*occupational ELF-EMF was not associated with an increased risk for meningioma*" (Carlberg et al., 2018, p. 1). Carlberg et al. (2020) included 310 cases of acoustic neuroma and 3,485 controls; similarly, the authors reported no statistically significant associations between acoustic neuroma and either average or cumulative magnetic-field exposure, regardless of the exposure period examined (1 to 14 years or 15+ years). The authors concluded that "*occupational ELF-EMF was not associated with an increased risk for acoustic neuroma*" (Carlberg et al., 2020, p. 1).

Carles et al. (2020) conducted a case-control study to investigate the association between residential proximity to power lines and brain tumor development among adults in France, from 1965 to 2006. The authors included 490 cases (gliomas and meningiomas combined) and 980 controls in their study. Exposure was assessed using the distance from the residence to the nearest power line and the voltage of the power lines as surrogate indicators of magnetic-field exposure. Several statistically significant associations were reported, although the associations were not consistent across brain tumor types or exposure metrics, and no clear exposure-response trend was observed. Statistically significant associations were reported between living < 50 meters from power lines of any voltage for more than 15 years and all brain tumors (OR: 4.33; 95% CI: 1.11–16.9), as well as meningiomas (OR: 8.53; 95% CI: [1.48–49.17]); between ever living < 50 meters from a power line of any voltage and glioma (OR: 4.96; 95% CI: 1.56–15.77); and between ever living < 50 meters from a high-voltage power line (< 200 kV) and both glioma (OR: 4.96; 95% CI:1.56–15.77) and all brain tumors (OR: 2.94; 95% CI:1.28–6.75). No statistically significant associations were observed between any tumor type and living < 50 meters from very-high-voltage power lines (≥ 200 kV) or living near power lines of any voltage for more than 5 years and more than 10 years. In addition, no statistically significant associations were observed for assessed magnetic-field exposure ≥ 0.3 μT [3 mG]). Souques et al. (2020) highlighted several methodological limitations in the Carles et al. (2020) study, including the potential for exposure misclassification due to inaccuracies of the geolocation method used to ascertain residential distance to power lines and the study's failure to account for underground lines, which would result in lower exposure levels, and concluded that due to these limitations, the results of the Carles et al. (2020) study were "*meaningless and unusable*" (Souques et al., 2020, p. 2).

Summary of research on adult brain cancer

Recent studies continue to provide no support for an association between magnetic-field exposures and development of brain cancer. As mentioned above, the most recent SCENIHR report states that, overall, studies on "*adult cancers show no consistent associations*" (SCENIHR, 2015, p. 158).

5.5 Breast cancer

While the WHO 2007 report concluded that breast cancer is likely not related to ELF magnetic-field exposure and that the "*more recent studies have convincingly shown no association with exposure to ELF magnetic fields*" and suggested that "*further research into this association should be given very low priority*," epidemiologic studies have continued to be published in this area (WHO, 2007, p. 18). Several occupational epidemiologic studies of female and male breast cancers provided no support for an association between ELF magnetic-field exposure and breast cancer development (Sorahan, 2012; Li et al., 2013; Koeman et al., 2014; Grundy et al., 2016). Two meta-analyses for female breast cancer (Chen et al., 2013; Zhao et al., 2014b) both reported a weak but statistically significant risk increase and concluded that ELF magnetic fields might be related to breast cancer development. This conclusion, which is contrary to the conclusion of the WHO and other risk assessment panels, may be explained by the reliance on earlier and methodologically less advanced studies in these meta-analyses. A meta-analysis for male breast cancer (Sun et al., 2013) showed a weak but statistically significant association between male breast cancer and estimated exposure to ELF magnetic field; methodological limitations, the small number of cases in the individual studies, and the potential for publication bias may contribute to these findings.

Recent studies on breast cancer (December 1, 2017 through January 31, 2022)

No published epidemiologic studies examining the potential relationship between ELF magnetic fields and breast cancer development were identified within the period of the literature search.

Summary of research on breast cancer

Since no new published studies were identified in the literature search, the conclusion that there is no association between ELF magnetic fields and breast cancer, as expressed by the WHO and other reviewing agencies, continues to be valid. The SSM concluded in two recent annual reports that, with respect to female breast cancer, "*now it is fairly certain that there is no causal relation with exposure to ELF magnetic fields*" (SSM, 2016, p. 7), and with respect to male breast cancer, "*[t]o date, there is no established link between ELF-MF [magnetic field] exposure and breast cancer in men*" (SSM, 2018, p. 49).

5.6 Neurodegenerative diseases

The WHO 2007 report concluded that the evidence was inadequate to link any of the examined neurodegenerative diseases to magnetic-field exposure and recommended further research in this area. In response to these recommendations, a number of epidemiologic studies of neurodegenerative diseases, mostly of Alzheimer disease and ALS, have been published in recent years. As summarized in Exponent (2017), occupational exposure to ELF magnetic fields and its potential association with neurodegenerative diseases have been evaluated in a number of recent epidemiologic studies (McCormick et al., 1999; Brouwer et al., 2015; Huss et al., 2015a; Koeman et al., 2015; van der Mark et al., 2015; Koeman et al., 2017; Pedersen et al., 2017). Overall, these studies did not provide consistent and convincing support for an association. Recent meta-analyses of published studies on ALS and Parkinson's disease reported no or only weak associations with occupational exposure to ELF magnetic fields (Zhou et al., 2012; Vergara et al., 2013; Capozzella et al., 2014; Huss et al., 2015b; Gunnarsson and Bodin, 2017). These authors also concluded that potential within-study biases, evidence of publication bias, and uncertainties in the various exposure assessment methods greatly limit inference for an association, if any, between occupational exposure to magnetic fields and neurodegenerative diseases.

Recent studies on neurodegenerative diseases (December 1, 2017 through January 31, 2022)

Cohort studies

Sorahan and Nichols (2022) investigated magnetic-field exposures and mortality from motor neuron disease [MND] in a large cohort of employees of the former Central Electricity Generating Board of England and Wales. The study included nearly 38,000 employees first hired between 1942 and 1982 and still employed in 1987; estimates of exposure magnitude, frequency, and duration were calculated using data from the power stations and the employees' job histories (Renew et al., 2003). Mortality from MND in the total cohort was observed to be similar to national rates. No statistically significant trends were observed with lifetime, recent, or distant magnetic-field exposure; statistically significant associations were observed for some categories of recent exposure. The authors concluded that their study "*does not indicate that occupational lifetime magnetic field exposures are a risk factor for MND but the possible role of recent exposures would be worth investigating in the other available studies*" (Sorahan and Nichols, 2022, p. 188).

Case-control studies

Checkoway et al. (2018) investigated the association between Parkinsonism[9] and occupational exposure to several agents, including endotoxin, solvents, shift work, and magnetic fields, among female Shanghai textile workers. The study included 537 retired cotton factory workers who were at least 50 years of age, and 286 age-matched controls who were retired cotton factory workers not exposed to cotton dust (which was used to define endotoxin exposure). Exposure to magnetic fields was assessed using a JEM. The authors reported no statistically significant associations between occupational exposure to magnetic fields and Parkinsonism. Statistically significant associations were also not observed with endotoxin, shift work, or solvent exposure.

Gervasi et al. (2019) conducted a case-control epidemiologic study to evaluate the relationship between residential proximity to overhead power lines and risk of Alzheimer’s disease and Parkinson’s disease in Italy. The study included 9,835 cases of Alzheimer’s dementia and 6,810 cases of Parkinson’s disease; 4 controls were matched to each case on sex, year of birth, and municipality of residence. Exposure assessment was based on residential distance from the nearest overhead power line (> 30 kV). The authors reported a weak, statistically not significant association between residences within 50 meters of overhead power lines and both Alzheimer’s disease (OR: 1.11; 95% CI: 0.95–1.30) and Parkinson’s disease (OR=1.09; 95% CI: 0.92–1.30). The study’s strengths include the large study population and the inclusion of potential confounders. The characterization of exposure using residential distance to power lines, however, is a primary limitation of the study.

Peters et al. (2019) assessed the potential relationship between occupational exposure to both ELF magnetic fields and electric shock with ALS in a multi-country European case-control study. The study included 2,704 cases and 1,323 controls; occupational exposure was assessed using a JEM. Statistically significant associations were observed between ALS and ever having been exposed above background levels to either magnetic fields (OR: 1.16; 95% CI: 1.01, 1.33) or electric shocks (OR: 1.23; 95% CI: 1.05, 1.43). No clear exposure-response trend was observed, however, with exposure duration or cumulative exposure.

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[9] Parkinsonism is defined by Checkoway et al. (2018) as “*a syndrome whose cardinal clinical features are bradykinesia, rest tremor, muscle rigidity, and postural instability. Parkinson disease is the most common neurodegenerative form of parkinsonism*” (p. 887).

Filippini et al. (2020) conducted a case-control study, including 95 cases and 1,235 controls, to evaluate the association between ALS and various environmental and occupational factors, including electromagnetic fields in Italy. Questionnaire-based information was used to assess occupational and residential exposure to "Electric and Electronic Equipment" and "Electromagnetic fields" (Filippini et al., 2020, p. 5). The authors reported a statistically significant association between ALS and proximity to overhead power lines (OR: 2.41; 95% CI:1.13–5.12). The association between ALS and occupational exposure to EMF was not statistically significant; occupational use of electric and electronic equipment was associated with a statistically non-significant decreased risk of ALS development. The study's limitations include the possibility of selection bias due to the low overall response rate (< 20%) and the potential for exposure misclassification as a result of reliance on a self-reported information to assess exposures.

Grebeneva et al. (2021) evaluated morbidity among electric power company workers in Kazakhstan. The authors included three groups of "*exposed*" workers who worked at electric substations (a total of 161 workers) and controls "*who were not associated with exposure to electromagnetic fields (114 people*)." Morbidity was assessed "*based on analyzing the sick leaves of employees*" from 2010 to 2014 and expressed as "*incidence rate per 100 employees*." The authors reported higher "*incidence rate*" of "*diseases of the nervous system*" in two of the exposed categories compared to the non-exposed group. No meaningful conclusions from the study could be drawn, however, because no specific diagnoses within "*diseases of the nervous system*" were presented in the paper. The study also had a small sample size and short follow up period. In addition, no measured or calculated magnetic-field levels were presented by the authors.

Chen et al. (2021) conducted a case-control study to assess the association between occupational exposure to electric shocks, magnetic fields, and MND, including ALS, in New Zealand. The study included 319 cases and 604 controls; exposure was assessed based on the participants' occupational history obtained using questionnaires and previously developed JEMs for electric shocks and magnetic fields. The authors reported no association between MND and exposure to magnetic fields when examining any of the exposure metrics (e.g., ever/never exposed, duration of exposure, cumulative exposure level). Positive associations were reported between MND and working a job with potential for electric shock exposure.

Meta-analyses and pooled analyses

Gunnarsson and Bodin (2018) conducted a meta-analysis of occupational risk factors for development of ALS and reported statistically significant associations between occupational exposure to magnetic fields and ALS (RR: 1.23; 95% CI: 1.04, 1.45) and between jobs that involve working with electricity and ALS (RR: 1.16; 95% CI: 1.00, 1.35). The authors noted a "*slight*" publication bias and some study heterogeneity (Gunnarsson and Bodin, 2018, p. 10). Significant associations were also reported between ALS and heavy physical work (RR: 3.98; 95% CI: 2.04–7.77), exposure to metals (including lead) and chemicals (including pesticides) (RR: 1.19; 95% CI: 1.07–1.33) and working as a nurse or physician (RR: 1.18; 95% CI: 1.05–1.34). Gunnarsson and Bodin (2019) updated their previous meta-analysis (Gunnarsson and Bodin, 2018) to also include Parkinson's disease and Alzheimer's disease. A statistically significant association was reported between exposure to magnetic fields and ALS (RR: 1.26; 95% CI: 1.07, 1.50) and Alzheimer's disease (RR: 1.33; 95% CI: 1.07, 1.64); no association was observed for Parkinson's disease. When the authors combined the studies of ALS and Alzheimer's disease, a stronger association with magnetic fields was observed in those studies published prior to 2005 compared to studies published more recently, and the authors opined that there is "*an evident publication bias*" in the studies published before 2005.

Huss et al. (2018) reported a weak overall association between ALS and estimated ELF magnetic-field levels (sRR: 1.14; 95% CI: 1.00, 1.30) in their analysis of 20 epidemiologic studies; a somewhat stronger association was observed within a subset of six studies with full occupational histories (sRR: 1.19; 95% CI: 1.03, 1.37) compared to studies where occupation was available only at certain time points (sRR: 1.08; 95% CI: 0.90, 1.29). The authors reported, however, substantial heterogeneity among studies, evidence for publication bias, and the lack of a clear exposure-response relationship between estimates of ELF magnetic fields and ALS. Limitations also include differences between studies regarding access to full occupational history and disease ascertainment method.

Jalilian et al. (2018) conducted a meta-analysis of 20 epidemiologic studies of occupational exposure to ELF magnetic fields and Alzheimer's disease and reported a moderate, but statistically significant, overall association for Alzheimer's disease (sRR: 1.63; 95% CI: 1.35–1.96), with weaker associations in cohort studies than in case-control studies. The authors also reported substantial heterogeneity among studies, and evidence for publication bias. Pooling results from studies with "*higher risk*" of bias, as assessed by the authors, resulted in stronger associations, suggesting that bias in the studies likely contributed to the reported associations.

Röösli and Jalilian (2018) reported no statistically significant associations in their analysis of combined data from five epidemiologic studies examining residential exposure to ELF magnetic fields from high-voltage power lines and ALS.

Huang et al. (2020) conducted a meta-analysis of 43 epidemiologic studies to investigate potential occupational risk factors for dementia or mild cognitive impairment. The authors included five cohort studies and seven case-control studies related to magnetic-field exposure. Positive associations were reported between dementia and work-related magnetic-field exposures in both types of studies (RR: 1.26; 95% CI: 1.01–1.57, for the cohort studies, and RR: 1.30; 95% CI: 1.06–1.60, for the case control studies). The authors, however, provided no information on the occupations held by the study participants, their magnetic-field exposure levels, or how magnetic-field levels were assessed. The authors also reported a high level of heterogeneity among studies. This analysis adds little to the weight of the evidence for an association between dementia and magnetic fields due to its limitations.

Filippini et al. (2021) conducted a meta-analysis to assess the dose-response relationship between residential exposure to magnetic fields and ALS. The authors identified six ALS epidemiologic studies that assessed exposure to residential magnetic fields by either distance from overhead power lines or magnetic-field modelling. They reported a decrease in risk of ALS in the highest exposure categories for both distance-based (sRR: 0.87; 95% CI: 0.63–1.20) and modeling-based exposure estimates (sRR: 0.27; 95% CI: 0.05–1.36). The authors also reported that their dose-response analyses "*showed little association between distance from power lines and ALS*"; the data was too sparse to conduct a dose-response analysis for modelled magnetic-field estimates. The authors noted that their study was limited by small sample size, the potential for residual confounding, and by "*some publication bias*."

Jalilian et al. (2021) conducted a meta-analysis of occupational exposure to ELF magnetic fields and electric shocks and development of ALS, including 27 studies from Europe, the United States, and New Zealand. A weak statistically significant association was reported between magnetic-field exposure and ALS (sRR: 1.20; 95% CI: 1.05, 1.38); no association was observed between electric shocks and ALS. "*Moderate to high*" heterogeneity and indications of publication bias was identified for the studies magnetic-field exposure and ALS and the authors noted that "*the results should be interpreted with caution*" (Jalilian et al., 2022, p. 1).

Summary of research on neurodegenerative diseases

In recent years, multiple studies have examined the potential relationship between EMF, electric shocks, and neurodegenerative diseases. Compared to earlier studies, many of these more recent studies represented methodological improvements (e.g., increased sample size, improved exposure assessment, inclusion of incidence cases). Despite of these methodological improvements, the overall evidence from these studies provided no consistent or convincing support for a causal association. The most recent SCENIHR report (2015) concluded that newly published studies "*do not provide convincing evidence of an increased risk of neurodegenerative diseases, including dementia, related to ELF MF [magnetic field] exposure*" (SCENIHR, 2015, p. 186).

5.7 Summary of *in vivo* research related to carcinogenesis

As summarized in Section 3, regarding *in vivo* studies of carcinogenesis, the WHO 2007 report concluded, "*[o]verall there 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*" (WHO, 2007, p. 322). More recently, SCENIHR concluded in their 2015 review of the literature that, "*[p]reviously SCENIHR (2009) concluded that animal studies did not provide evidence that exposure to magnetic fields alone caused tumours or enhanced the growth of implanted tumours. The inclusion of more recent studies does not alter that* *assessment. In addition, these studies do not provide further insight into how magnetic fields could contribute to an increased risk of childhood leukaemia*" (SCENIHR, 2015, p. 161).

Research published during the review period of this report (December 1, 2017 to January 31, 2022) do not provide sufficient evidence to alter the conclusions of these agencies' reviews. Large-scale, long-term cancer bioassays, considered the gold standard for identifying carcinogens in animals, reported that lifetime exposure to magnetic fields does not initiate or promote tumor development in rodents. The quality of most studies, however, leaves much to be improved, as noted in an ICNIRP (2020) review of the research related to potential health effects of magnetic-field exposure, in which they concluded, "*further studies on mechanisms and biological data from childhood leukemia experimental models are recommended*" (ICNIRP, 2020, p. 535).

6 Exposure Guidelines

Following a thorough review of the relevant research, scientific agencies develop exposure standards to protect against known health effects. The major purpose of a weight-of-evidence review is to identify the lowest exposure level below which no health hazards have been found (i.e., a threshold). Exposure limits are then set well below the threshold level to account for any individual variability or sensitivities that may exist.

Several scientific organizations have published guidelines for exposure to EMF based on acute health effects that can occur at very high field levels. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) reviewed the epidemiologic and experimental evidence through 1997 and concluded that there was insufficient evidence to warrant the development of standards or guidelines on the basis of hypothesized long-term adverse health effects such as cancer; rather, the guidelines put forth in their 1998 document set limits to protect against acute health effects (i.e., the stimulation of nerves and muscles) that occur at much higher field levels (ICNIRP, 1998). ICNIRP issued a revised set of guidelines for the frequency range from 1 Hz to 100 kilohertz in 2010 (ICNIRP, 2010). The revised ICNIRP guidelines recommend a screening value of 2,000 mG for the general public and an occupational exposure screening value of 10,000 mG (ICNIRP, 2010). If exposures exceed these screening values, then additional dosimetry evaluations are needed to determine whether basic restrictions on induced current densities are exceeded.

The International Committee on Electromagnetic Safety (ICES) also recommends limiting magnetic-field exposure at high levels because of the risk of acute effects, although their guidelines are higher than ICNIRP's guidelines at 60 Hz. ICES recommends a residential exposure limit of 9,040 mG and an occupational exposure limit of 27,100 mG (ICES, 2019, 2020). Both guidelines incorporate large safety factors.

The ICNIRP and ICES guidelines provide guidance to national agencies and only become legally binding if a country adopts them into legislation. The WHO strongly recommends that countries adopt the ICNIRP guidelines, or use a scientifically sound framework for formulating any new guidelines (WHO, 2006).

There are no national or state standards in the United States limiting exposures to ELF fields based on health effects. Only two states, Florida and New York, have enacted standards to limit magnetic fields at the edge of the ROW from transmission lines (150 mG and 200 mG, respectively) (NYPSC, 1978; FDER, 1989; NYPSC, 1990; FDER, 1996). The basis for limiting magnetic fields from transmission lines in Florida and New York was to maintain the status quo so that fields from new transmission lines would be no higher than those produced by existing transmission lines.

Table 2. Screening guidelines for EMF exposure

Exposure (60 Hz)	Electric field (kV/m)	Magnetic field (mG)
ICNIRP		
Occupational	8.3	10,000
General Public	4.2	2,000
ICES		
Occupational	20	27,100
General Public	5*	9,040

Source: ICNIRP (2010); ICES (2019, 2020)

*Within power line ROWs, the guideline is 10 kV/m under normal load conditions.

7. Precautionary Measures

A precautionary policy for risk management of possible, but unproven, adverse effects emerged in Europe in the 1970s regarding environmental issues. The *precautionary principle* refers to the idea that, when evidence does not support the suggestion that an exposure is the cause of a particular disease but where a risk is perceived, precautionary measures may be taken that are proportional to the perceived level of risk, with science as the basis for measuring that risk. A key element of precautionary approaches is the recognition that a real risk from the exposure may not exist, and its necessary corollary is that the reduction of exposure may not reduce the level of adverse effects in the population.

A variant of the precautionary principle called "*prudent avoidance*" has been favored as a policy option for EMF by some national and local governments. The WHO describes this as "*using simple, easily achievable, low to modest (prudent) cost measures to reduce individual or public EMF exposure, even in the absence of certainty that the measure would reduce risk*" (WHO, 2002).

The scientific evaluation completed by the WHO also discusses general policy strategies for risk management, and provides a summary table of different worldwide policy strategies specifically for EMF exposure in the general public (WHO, 2007, Chapter 13). The WHO recommended the following precautionary measures:

- Countries are encouraged to adopt international science-based guidelines.
- 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 reductions 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 programs to reduce the uncertainty of the scientific evidence on the health effects of ELF field exposure.

(Adapted from WHO 2007, pp. 372-373)

In summary, the general recommendation of the WHO is as follows:

> *Countries are encouraged to adopt international science-based guidelines. In the case of EMF, the international harmonization of standard setting is a goal that countries should aim for (WHO, 2006). If precautionary measures are considered to complement the standards, they should be applied in such a way that they do not undermine the science-based guidelines* (WHO, 2007, p. 367).

8. Summary

Recent studies published on ELF EMF and health have not provided sufficient evidence to alter the basic conclusion of the WHO—that the research does not confirm that electric fields or magnetic fields are a cause of cancer or any other disease at the levels we encounter in our environment. The weak statistical association between high, average magnetic fields and childhood leukemia reported in two pooled analyses in 2000 (Ahlbom et al., 2000; Greenland et al., 2000) has not been appreciably strengthened by subsequent research. Rather, the strength of the association has diminished over time, and the latest pooled analysis of epidemiologic studies published on this topic in the past 10 years reported "*no association between MF [magnetic fields] and childhood leukemia*" (Amoon et al., 2022). Thus, the previously reported association in some epidemiologic studies remains unexplained and is unsupported by *in vivo* experimental studies. Research on other cancer and non-cancer outcomes evaluated in this report provided no substantial new information to alter the previous conclusions that the evidence is inadequate to conclude that ELF EMF exposure is harmful at typical environmental levels. While the large body of existing research does not confirm any likely harm associated with ELF EMF exposure at low levels, research on this topic will continue to reduce remaining uncertainty.

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