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# Overview of Scientific Assessments of Research on ELF EMF and Health, and Epidemiologic Studies, 2007-2015

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# Executive Summary

Since the late 1970s, potential health effects related to electric and magnetic fields (EMF) in the extremely low frequency (ELF) range associated with power systems and electrical devices have been the focus of extensive scientific research. Because of the amount and complexity of the scientific studies in this area, comprehensive evaluations of the available scientific evidence have been performed for health and scientific agencies by panels comprised of independent scientists with expertise in relevant scientific disciplines.

In Ireland, the scientific research was evaluated and a report on this topic was prepared by a group commissioned by the Department of Communications, Marine and Natural Resources (DCMNR) in 2007. The DCMNR report, similar to earlier evaluations performed for national and international agencies, did not conclude that the evidence confirms any adverse health effects of exposure to ELF EMF at levels encountered around electrical facilities and other sources.

This report summarizes the conclusions of a number of reviews that have been published since 2007 by other scientific panels, including those of the International Commission on Non-Ionizing Radiation Protection; the Swedish Radiation Protection/Safety Authority; the Federal, Provincial, Territorial Radiation Protection Committee of Canada; and the Ministry of Health of New Zealand. These reviews all reached conclusions consistent with those of the DCMNR report and did not conclude that any adverse health effects in relation to EMF exposure have been established by the accumulated scientific research results. In 2015, the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) issued its opinion report in which the Committee concluded that research published between 2009 and 2014 did not confirm any adverse health effects of EMF exposure.

The conclusions of the 2015 SCENIHR review were consistent with the conclusions expressed in earlier reviews and with the conclusions of the DCMNR report and the Environmental Health Criteria report of the World Health Organization. Overall, the SCENIHR report did not conclude that the evidence confirms the existence of any adverse health effects. With respect to

childhood leukemia, the SCENIHR recognizes the reported epidemiologic associations, but due to the lack of known mechanism and the lack of supportive animal data, it does not consider the association to be causal. Altogether, a comparison of the DCMNR and SCENIHR reviews shows that while much additional research has been published over the 8-year period between publication, the main conclusions of these reviews are quite consistent—the scientific evidence does not establish that ELF EMF at levels found in everyday environments pose a public health or safety threat.

An alternative view espoused by a self-assembled group of scientists who authored the BioInitiative Report (BIR) is also discussed. As several international agencies pointed out, the BIR did not follow the methods of a standard weight-of-evidence scientific assessment and attributed importance mostly or only to studies showing some effects and discounted those that did not. Also contrary to previous agency reports, the conclusions expressed in BIR were not consensus opinions but were the opinions of the authors of the various report chapters. Because BIR did not follow scientific methods in its assessment of the evidence, its conclusions cannot be considered as scientifically valid.

The most debated issue addressed in these assessments is the role of human epidemiologic studies of ELF EMF exposure in health risk assessments and the interpretation of the studies to date. Therefore, this report also discusses how scientific evidence, including epidemiologic studies, is evaluated and presents an overview of ELF EMF epidemiologic studies published during the period between the DCMNR and SCENIHR reports.

# Introduction

Electricity is an indispensable part of a modern society. The electricity we use in our homes and businesses, or for transportation, education, health care, and other purposes, is generated, transmitted, and distributed via the electric system. In Ireland the electric grid includes over 6,400 kilometers of high-voltage transmission lines operated by EirGrid.

Since the late 1970s, extensive scientific research has been carried out to investigate whether there are potential health effects in relation to the extremely low frequency (ELF) electric and magnetic fields (EMF) that are associated with the generation, transmission, and use of electricity. The large volume of scientific results that accumulated over almost four decades has been repeatedly and systematically reviewed by a number of authoritative national and international health, scientific, and government agencies. In Ireland the responsible government agency, the Department of Communications, Marine and Natural Resources (DCMNR), assembled a panel of scientists in 2007 to review the available scientific evidence and published its findings (DCMNR, 2007). Overall, the DCMNR report concluded that "[n]o adverse health effects have been established below the limits suggested by international guidelines." Its recommendations, however, also included some precautionary measures "to keep exposures to people low." Their precautionary recommendation was made in response to the "limited scientific evidence of an association" from childhood leukemia epidemiologic studies, even though the DCMNR panel thought it "unlikely that ELF magnetic fields cause leukaemia in children" when epidemiologic results were considered together with the unsupportive laboratory animal studies.

Since 2007, continued research efforts worldwide have resulted in a number of new scientific publications in this area. As part of its commitment to ensure that the operation of its transmission lines is managed consistent with scientifically-based recommendations and policies, EirGrid requested Exponent to review the relevant scientific literature published following 2007 and evaluate whether the newly published scientific data necessitates any changes to the earlier conclusions expressed in the 2007 DCMNR report. In the following sections we provide background information on the nature, characteristics, and sources of EMF;

provide information on how relevant scientific research is conducted and evaluated with respect to potential environmental and health effects; review some of the main evaluations conducted by multidisciplinary expert panels on behalf of health, scientific, and government organizations; and provide a comprehensive overview of the relevant epidemiologic literature published between 2007 and 2015. Since the main area of debate involves some of the associations reported in epidemiologic studies, the epidemiologic literature comprises the focus of this overview.

# Electric and Magnetic Fields – Nature and Characteristics

EMF is associated with both natural and manmade sources. For example, the earth is a source of naturally occurring geomagnetic field that has been used for navigation for centuries and there is naturally occurring electric field present in the atmosphere that can increase to very high levels and result in lightning during thunderstorms. Manmade sources include, for example, the electricity grid that is associated with ELF fields, or communications equipment that is a source of radiofrequency fields.

EMF is characterized by magnitude, direction, and frequency. Frequency is the number of times fields change direction and complete a full cycle per second. Frequency is expressed in Hertz (Hz) or multiples of Hz, such as kilohertz (kHz), megahertz (MHz), or gigahertz (GHz). Electromagnetic energy with various frequencies forms the electromagnetic spectrum, which includes static fields (0Hz, associated with direct current) and the ELF (3-300 Hz) at the lower end; radio waves, microwaves, and visible light, with frequencies in the several hundred kHz to MHz and GHz in the mid-range; and X-rays and gamma rays with frequencies of billions of Hz at the upper end. Frequency is related to the energy level of the fields, which is a key factor in determining interactions with objects and living things. High frequency fields have high energy and are able to ionize atoms, that is, they are able to dislodge electrons from their path around their atomic nucleus, potentially causing damage in living cells. Frequencies in the radio wave and microwave range (radiofrequency) may be able, at very high levels, to result in tissue heating. Lower frequency fields, however, such as ELF, have very little energy and have no ionizing or tissue-heating effects. Electricity in Ireland is primarily used as alternating current (AC) at a frequency of 50Hz, and is associated with 50Hz EMF, which is part of the ELF range of the electromagnetic spectrum.

Electricity is associated with two types of fields—electric fields and magnetic fields. Electric fields are generated by voltage, and are measured in units of volts per metre (V/m) or kilovolts per metre (kV/m), where 1 kV/m is equal to 1,000 V/m. Magnetic fields are created by the flow of electric current, and are measured in Tesla (T) or microTesla (μT), where 1 T is equal to

1,000,000 μT.[1] In outdoor environments, distribution and transmission lines are examples of EMF exposure sources. At 30 metres (m) from the highest voltage transmission lines (i.e., 400 kV lines in Ireland), electric-field levels may typically reach 1 kV/m or so and magnetic-field levels may typically reach a few μT; these fields, however, quickly diminish away from the lines.[2] In indoor environments, electric appliances, tools, and equipment, and electrical wiring in buildings are the most common sources of EMF. Magnetic-fields levels close to some electric tools and equipment may reach over 100μT, which diminish to much lower levels within several metres. Residential exposure surveys indicate that magnetic-field exposure in homes varies widely 0.01-0.2μT in the general population.[3] Average exposure could be higher in certain occupational environments. While electric fields are easily shielded by conductive objects, such as building materials and trees, magnetic fields are not. Both electric and magnetic fields, however, quickly diminish with distance away from the source.

[1] In some parts of the world, such as North America, magnetic flux density is reported in units of milligauss (1 μT is equal to 10 milligauss).

[2] http://www.eirgrid.com/media/Information%20on%20Electric%20and%20Magnetic%20Fields.pdf%20%5B3,180KB%5D.pdf

[3] https://www.gov.uk/government/publications/electric-and-magnetic-fields-sources-and-exposure/electric-and-magnetic-fields-sources-and-exposure

# Scientific Research Process

To learn about potential effects of environmental exposures on human health, scientists conduct research studies that may be broadly grouped into three general categories: epidemiologic studies, laboratory animal studies, and laboratory studies using cells and tissues. In addition, if an exposure is judged harmful, exposure assessment and exposure characterization in the population also play a role in determining the overall potential impact of that exposure on public health.

Epidemiologic studies examine the occurrence and distribution of diseases and their potential causes, such as various genetic conditions and environmental exposures, in human populations. The most common and most useful epidemiologic studies could be broadly categorized into two main types: case-control studies and cohort studies.[4] Case-control studies identify cases of a particular disease (e.g., leukemia cases in a certain geographic region during a specific calendar time) and compare the distribution of exposure among these cases to that among controls, that is people without the same disease. Controls are ideally a representative sample of the population at risk, that is, individuals who are at risk of getting the disease and would have been included in the study as cases had they developed the disease during the study period. In a case-control study, epidemiologists calculate an odds ratio (i.e., the ratio of the odds of being exposed among the cases to the odds of being exposed among the controls) as an estimate of the association between exposure and disease. If the odds ratio is larger than 1.0, it may indicate an association between exposure and disease; and if the odds ratio is less than 1.0, it may indicate a potentially protective effect of the exposure. The main advantage of a case-control design is that it can be efficiently used for the study of rare diseases. The main disadvantage is that it estimates exposure for cases and controls retrospectively, which may results in exposure misclassification, particularly, if exposure may change over time and determination of exposure status relies on subjects' memories or recall. Another main limitation of case-control studies is the potential for selection and participation bias. Inappropriate specification of a sampling frame for controls (for example, when the source population for controls does not represent the actual population at

[4] There are other types of epidemiologic studies but they are less commonly used or less informative.

risk) or biased selection and participation may also result in distorted effect estimates in the study.

The conduct of cohort epidemiologic studies starts with the identification of the study population, which includes individuals free of the disease under investigation, and with the determination of the exposure status of all members of the study population. Then the investigators follow the study population to examine disease frequency among exposed and unexposed subjects. Epidemiologists calculate relative risk by comparing the risk of disease development among the exposed subject to that among the unexposed subjects. Similar to the odds ratio, if the relative risk is above 1.0, it might indicate an association between exposure and disease and if it is below 1.0, it might indicate a potentially protective effect. The main advantages of epidemiology cohort studies include the prospective nature and follow up, that exposure is determined before disease development, and the reduced potential for selection bias. The main disadvantage of the cohort design is its higher cost that may render it infeasible or prohibitively costly, particularly for rare diseases that might require the inclusion of very large populations and long follow-up periods. Both study designs are subject to random variability and the potential for confounding by another risk factor for the disease that may be associated with the exposure of interest in the study.

Laboratory animal studies, also called *in vivo* studies, expose groups of animals, mostly rodents (rats and mice) to the agent under investigation and compare the rate of disease development among the exposed animals to that among the unexposed animals. In these studies, the researchers can randomly assign animals to various exposure levels, and can control for other extraneous factors that may influence disease development among the animals (e.g., genetic and environmental factors); this, in principle, can isolate the effect of the exposure from all other variables. In laboratory animal studies, the effect of very high exposure levels (that may not be encountered in environmental scenarios) or potentially harmful exposures may also be examined, which cannot be done in human populations due to ethical considerations. Responses to exposure at multiple intensity levels may allow the examination of a potential exposure-response relationship, which—if observed—may contribute further support for a causal interpretation. The main and obvious disadvantage of animal studies is that they do not study

humans, the main species of interest in human risk assessment. While there are uncertainties due to potential interspecies differences in size, shape, metabolism, and genetic background between laboratory animals and humans, animal studies remain invaluable tools in human risk assessment. For example, to date, all known carcinogens to humans that were appropriately tested also were shown to contribute to cancer causation in laboratory animal studies.

Laboratory studies of cells and tissues, also called *in vitro* studies, allow the direct observation of exposure effects on individual cells or groups of cells, and processes at the cellular level that could not be observed in intact organisms. Processes and effects that may be observed in isolated cells and tissues, however, may not necessarily occur in whole living animals or humans due to higher level regulatory processes that are also operating in the intact body.

# Evaluation of Scientific Research Results

## Weight of Evidence Review

When determining whether an environmental exposure may have adverse effects on human health, proper and generally accepted scientific methods, for example those recommended by the World Health Organization (WHO), call for the identification and evaluation of the entire available and relevant scientific literature before drawing conclusions. The process starts with the systematic identification of all published, peer-reviewed scientific articles reporting on the specific exposure and biological or health endpoints within the three main areas, including epidemiologic, *in vivo*, and *in vitro* studies. Each identified study is then reviewed for its strengths and limitations in order to assign a weight to that study. The weight that individual studies contribute to the overall assessment is not equal and no individual study can be the basis of scientific conclusions. Well-conducted studies with few limitations contribute more weight to the overall assessment than studies with poor methodology and major limitations. Studies with severe flaws in the design, analysis, or interpretation may not contribute any weight to an overall assessment. Scientists look for patterns in the overall evaluation to see if various studies with varying weights show similar results and whether they point to the same overall direction. First, studies are evaluated within the three main streams of evidence, and then they are evaluated in combination. Human risk assessments, as a result of their strengths and limitations discussed above, primarily rely on epidemiologic studies and then on laboratory animal studies, with *in vitro* studies contributing only secondary information related to potential biological mechanisms.

The weight of evidence evaluations are frequently guided by the criteria, or some adaptation of those, developed by Sir Austin Bradford Hill in the 1960s. Hill's criteria include considerations of the strength of the association in the individual studies, the consistency of the association within and across studies, the specificity of the exposure for the outcome, the temporal relationship between the exposure and the outcome, evidence for an exposure-response relationship, the biological plausibility of the hypothesized cause-and-effect association, coherence with our current scientific understanding about the natural history and biology of the

disease, support from experimental or semi-experimental studies, and the existence of established analogous associations. While Hill's criteria were initially recommended to assess epidemiologic evidence, they are readily applicable to the other research areas as well. While none of the proposed criteria represent "… *indisputable evidence for or against the cause-and-effect*…," as explained by Sir Austin Bradford Hill himself, the more consistently the epidemiologic evidence meets these guidelines, the more convincing the evidence for a cause-and-effect relationship (Hill, 1965, p. 299).

In some instances, the evidence clearly supports a causal conclusion (e.g., smoking and lung cancer), but in most cases the picture is not as clear and some uncertainty remains. In other instances, while the preponderance of the evidence may not support an association, science, in general, is not able to prove the absence of a potential effect, thus, some residual uncertainty remains even for well-studied and predominantly negative exposure-disease relationships. In such situations, scientific panels typically conclude that the research is inadequate or limited to support a particular conclusion. Scientists may recommend further research in such situations to further reduce remaining scientific uncertainties, which the public may interpret as indicating or expressing concern even if the evidence is largely negative and a potential causal relationship is unlikely.

The International Agency for Research on Cancer (IARC) has developed a classification system for evaluation of carcinogenicity that is commonly used and also adapted for non-cancer health outcomes and is based on weight-of-evidence evaluations (Appendix A – IARC Classification System). The IARC classification categorizes the overall evidence separately from human epidemiologic studies and laboratory animal studies into four groups, such as providing sufficient evidence, limited evidence, and inadequate evidence for carcinogenicity, or providing evidence suggesting lack of carcinogenicity. Based on the combination of the level of evidence from human and animal studies, the process then classifies the exposure in question into one of five categories: carcinogenic to humans (group 1); probably (group 2A) or possibly (group 2B) carcinogenic to humans; not classifiable (group 3); or probably not carcinogenic to humans (group 4).

# Reviews by Scientific Agencies

Since the publication of the DCMNR report in 2007, a number of evaluations have been published by national and international expert panels on behalf of scientific and government agencies around the world. While some of these evaluations included a comprehensive review and a weight-of-evidence assessment of the entire literature, some of them assessed the incremental change in evidence by reviewing only recent literature since a previous assessment, and others relied on reviews of previous assessments conducted by other expert panels. Below we provide a brief overview of the reports providing an evaluation of the evidence from 2007 onward.

## World Health Organization

To date the most comprehensive weight-of-evidence review of both cancer and non-cancer health outcomes and ELF EMF exposure has been published by the WHO, which released its Environmental Health Criteria (EHC) report on ELF EMF in 2007. Based on the overall evidence, the WHO EHC did not conclude that the ELF EMF is a cause or a probable cause of any cancer or non-cancer health outcome. The WHO, however, confirmed the earlier conclusion of IARC about the limited evidence from epidemiologic studies of childhood leukemia and ELF magnetic fields, which was overall not supported by the negative laboratory animal studies and the lack of known biophysical mechanisms to explain a potential carcinogenic effect. For all other childhood and adult cancers and all non-cancer health outcomes and ELF magnetic fields and for all health outcomes and ELF electric fields, the evidence was judged as inadequate (Appendix B – WHO Conclusions on Specific Health Outcomes). The conclusions of the WHO EHC were consistent with the conclusions of the DCMNR report and with earlier assessments and conclusions reached by the United States' National Institute of Environmental Health Sciences in 1999, the IARC in 2002, and the National Radiological Protection Board of Great Britain in 2004.

## Scientific Committee on Emerging and Newly Identified Health Risks

The Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) is the European Union's scientific committee that provides independent scientific opinions to guide

policies of the European Commission on emerging or newly-identified health and environmental risks and on broad, complex, or multidisciplinary issues requiring a comprehensive assessment of risks to consumer safety or public health and related issues. Its mandates also include scientific reviews of potential health effects associated with EMF, including ELF EMF. SCENIHR has periodically reviewed the evidence and issued opinions on EMF and health in 2007, 2009, and most recently in 2015. The conclusions of the 2015 SCENIHR review were consistent with the conclusions expressed in earlier reviews, with the WHO EHC, and with the conclusions of the DCMNR report (Appendix C – Comparison of DCMNR and SCENIHR). Overall, the SCENIHR report did not conclude that the evidence confirms the existence of any adverse health effects. With respect to childhood leukemia, the SCENIHR continues to recognize the observed epidemiologic association, but due to the lack of known mechanisms and the lack of supportive animal data, it does not consider it a causal association.

> *The new epidemiological studies are consistent with earlier findings of an increased risk of childhood leukaemia with estimated daily average exposures above 0.3 to 0.4 μT. As stated in the previous Opinions, no mechanisms have been identified and no support is existing from experimental studies that could explain these findings, which, together with shortcomings of the epidemiological studies prevent a causal interpretation* (SCENIHR, 2015, p.7).

## International Commission on Non-Ionizing Radiation Protection

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) is an independent organization of scientists from various disciplines with expertise in the field of non-ionizing radiation assembled from around the world. It provides scientific advice and guidance on the health and environmental effects of non-ionizing radiation to protect people and the environment from detrimental exposures to ELF EMF. As part of its mandate, ICNIRP develops scientifically-based exposure guidelines for exposure to EMF to protect public and worker health (Appendix D – ICNIRP Guidelines for 50 Hz). Its guideline recommendations for non-ionizing radiation are formally recognized by the WHO, the International Labor Organization, and the European Commission. ICNIRP developed its most recent guidelines for ELF EMF in

2010. Compliance with current ICNIRP guidelines ensures protection from established effects of ELF magnetic fields and electric fields (i.e., the direct stimulation of nerve and muscle tissue, the induction of retinal phosphenes, and surface electric-charge effects). In its evaluation of potential long term outcomes, including the epidemiologic evidence on cancer development, ICNIRP states that "[i]n general, the initially observed associations between 50–60 Hz magnetic fields and various cancers were not confirmed in studies designed to see whether the initial findings could be replicated" (ICNIRP, 2010, p. 823). With respect to potential effects on laboratory animals, ICNIRP concludes that "the animal cancer data, particularly those from large-scale lifetime studies, are almost universally negative" (ICNIRP, 2010, p. 823). In regard to childhood leukemia, ICNIRP concludes:

> *It is the view of ICNIRP that the currently existing scientific evidence that prolonged exposure to low frequency magnetic fields is causally related with an increased risk of childhood leukemia is too weak to form the basis for exposure guidelines. In particular, if the relationship is not causal, then no benefit to health will accrue from reducing exposure* (ICNIRP, 2010, p. 824).

## Swedish Radiation Protection/Safety Authority (SSI/SSM)

On behalf of the Swedish Radiation Protection Authority (SSI), and later the Swedish Radiation Safety Authority (SSM), the Scientific Council on Electromagnetic Fields has regularly reviewed scientific progress on EMF-related health research and has issued annual reports on EMF and health risks (SSI, 2007, 2008; SSM 2009, 2010, 2013, 2014). Similar to previous conclusions, the most recent report issued in 2015 did not conclude that any adverse health effects are caused by exposure to ELF EMF. With respect to childhood leukemia, the 2015 report states that, while a consistent epidemiologic association has been observed, a causal relationship has not been established. They also recommend further research on Alzheimer's disease and amyotrophic lateral sclerosis (ALS), as the authors consider a potential relationship with ELF EMF unresolved. With respect to adult cancer, the report states, "new studies do not change the view on the topic," and the evidence remains inadequate to support a conclusion of carcinogenicity (SSM, 2015, p. 50).

## European Health Risk Assessment Network on EMF Exposure

The European Health Risk Assessment Network (EFHRAN) was funded by the European Union with the objectives of monitoring, researching, and characterizing health risks related to EMF. In a 2012 EFHRAN report titled "Risk analysis of human exposure to electromagnetic fields," specific conclusions about the strength of evidence were reached with respect to potential relationships of ELF EMF to various health effects. The evidence for childhood leukemia was considered "limited." For all other adult and childhood cancers the evidence was concluded to be "inadequate," with the exception of breast cancer, for which the evidence suggested "lack of effect." For neurodegenerative diseases, reproductive outcomes, and symptoms the evidence was also judged "inadequate," while for cardiovascular diseases and "electrical hypersensitivity" the evidence, according to EFHRAN, suggested "lack of effect."

## Federal, Provincial, Territorial Radiation Protection Committee of Canada

The Federal, Provincial, Territorial Radiation Protection Committee (FPTRPC) is a Canadian intergovernmental Committee established to support Federal, Provincial, and Territorial radiation protection agencies in their respective mandates, to advance the development and harmonization of practices and standards for radiation protection within Federal, Provincial, and Territorial jurisdictions, and to communicate these to the people of Canada. The FPTRPC monitors the relevant scientific literature and conducted its own literature review in 2005 (FPTRPC, 2005). In 2008, the FPTRPC issued a statement that concluded the following with respect to EMF and health:

> *In summary, it is the opinion of the Federal-Provincial-Territorial Radiation Protection Committee that there is insufficient scientific evidence showing exposure to EMFs from power lines can cause adverse health effects such as cancer. Therefore, a warning to the public to avoid living near or spending time in proximity to power lines is not required (http://www.hc-sc.gc.ca/ewh-semt/radiation/fpt-radprotect/emf-cem-eng.php).*

> Accordingly, the Canadian Government and Health Canada are of the stated opinion that:
>
> *[e]xposure in Canadian homes, schools and offices present no known health risks,"* and that *"Health Canada does not consider that any precautionary measures are needed regarding daily exposures to EMFs at ELFs. There is no conclusive evidence of any harm caused by exposures at levels found in Canadian homes and schools, including those located just outside the boundaries of power line corridors (http://healthycanadians.gc.ca/healthy-living-vie-saine/environment-environnement/home-maison/emf-cem-eng.php).*

## New Zealand Ministry of Health Interagency Committee on the Health Effects of Non-Ionizing Fields

An interagency committee on the health effects of non-ionizing fields that was convened by the Ministry of Health of New Zealand evaluated, and summarized *"key findings from comprehensive reviews undertaken in recent years by national and international health and scientific bodies"*(MHNZ, 2015, p. v). Although the report states that *"much new research has been published since 2004,"* when the committee prepared its previous review, the current report concludes that the *"the picture is largely unchanged since publication of the WHO review in 2007*" (MHNZ, 2015, pp. vi, 10). The report did not conclude that, overall, any causal association has been demonstrated in association with exposure to ELF EMF. The report states that the results of the epidemiologic studies on childhood leukemia are not supported by results of laboratory research, and even if there were to be a causal relationship, it would only explain a small fraction of childhood leukemia cases.

## Alternative Views

As discussed above, none of the authoritative and properly-conducted scientific reviews by government or scientific agencies has concluded that the evidence confirms the existence of any health consequences in association with exposure to ELF EMF in our daily environments. There are, however, alternative views, which are not based on proper and rigorous evaluation of the

scientific evidence. Such an alternative view is represented by the BioInitiative Report (BIR). The BIR was authored by a self-organized group of individuals from academic institutions and public interest groups. They are collectively called the BioInitiative Working Group and do not work under the auspices of any government or recognized scientific organization. They published their initial report on the internet in 2007, and issued an updated report, also on the internet, in 2012. The conclusions of the BIR are contrary to the previously described weight-of-evidence reviews, and suggested that a number of health outcomes are causally linked to ELF EMF exposure and that the existing exposure limits for ELF EMF are insufficient because "effects are now widely reported to occur at exposure levels significantly below most current national and international limits" (BIR, 2012, Table 1-1). The BIR report did not follow the weight-of-evidence approach and attributed importance mostly or only to studies showing some effect and discounted those that did not. The BIR also differed from previous reports in that the conclusions were not developed as consensus opinions but were opinions of individual authors.

The BIR has been heavily criticized by several scientific agencies, including the Health Council of the Netherlands (HCN), the Australian Centre for Radiofrequency Bioeffects Research (ACRBR), the EMF-NET Steering Committee of the European Commission, and the IEEE's Committee on Man and Radiation. All of these agencies indicated that the BIR did not follow the methods of a standard weight-of-evidence review and, for this reason, its conclusions and recommendations were not convincing. In a two-page position statement on the BIR in 2008, the ACRBR wrote, "[a]s it stands it [BIR] merely provides a set of views that are not consistent with the consensus of science, and it does not provide an analysis that is rigorous-enough [*sic*] to raise doubts about the scientific consensus" (ACRBR, 2008). The EMF-NET opined that the BIR was "written in an alarmist and emotive language and the arguments have no scientific support from well-conducted EMF research" and "[t]here is a lack of balance in the report; no mention is made in fact of reports that do not concur with authors' statements and conclusions" (EMF-NET, 2007, p. 1). The HCN also questioned the motivation of the BIR authors for preparing the report, and they stated, "[u]pfront, therefore, the reason for writing the report was not to give an objective analysis of the current state of science, that would subsequently lead to recommendations. Instead, the aim was to present information to demonstrate why current standards are inadequate" (HCN, 2008, p. 3).

# Overview of Recent ELF EMF Epidemiology Research Literature

This section provides a brief overview of the epidemiologic literature on ELF EMF exposures published since 2007. Key studies in specific areas are discussed and a comprehensive list of epidemiologic studies published since 2007 to date for main cancer and non-cancer outcomes is provided (Appendix E). An assessment is made of whether these more recent research results, taken as a whole and together with previously available literature, offer any new insights that would alter conclusions reached by the DCMNR in their report issued in 2007, and compare these conclusions to those reached by the most-recent 2015 SCENIHR report.

## Childhood Cancer

### Conclusions of the DCMNR and WHO in 2007

Childhood cancer, particularly childhood leukemia, has been the main focus of ELF EMF health research for almost the past four decades following the initial publication in 1979 by Wertheimer and Leeper that reported an association between electrical wiring characteristics near the children's homes and occurrence of childhood cancer. The 2002 assessment of the evidence for carcinogenicity by the IARC scientific panel concluded that the statistical associations observed in some of the childhood leukemia epidemiologic studies could be considered as "limited" evidence. The association was not supported by laboratory animal studies, however, and no known biophysical mechanism was identified that could potentially explain a carcinogenic effect. Thus, the IARC panel classified ELF magnetic-field exposure as "possibly carcinogenic to humans." This classification implies that the reported association was considered credible, but chance, bias, and confounding could not be ruled out as an explanation, thus causality is not established. The evidence was not strong enough to classify ELF magnetic fields as either "carcinogenic" or "probably carcinogenic." The 2007 WHO report confirmed the IARC classification, concluding that studies published following the IARC evaluation had not provided new evidence to alter the conclusion. Similarly, the 2007 DCMNR report also recognized the "limited" evidence from childhood leukemia epidemiologic studies, which, however, they state, "… does not mean that ELF magnetic fields cause cancer, but the

possibility cannot be excluded," and that overall "it is unlikely that ELF magnetic fields cause leukemia in children" (DCMNR, 2007, p. 3). For all other childhood cancers, which primarily include brain cancers, the evidence was judged inadequate by IARC in 2002, which was confirmed by the reports of the DCMNR and the WHO in 2007.

## Key Recent Studies

Following up on two pooled analyses (Greenland et al., 2000; Ahlbom et al., 2000) that provided key input for the subsequent evaluations, including those by the IARC, the WHO, and the DCMNR, and to evaluate whether more recent studies provide new insight, a pooled analysis of childhood leukemia epidemiologic studies published between 2000 and 2010 was conducted in 2010 (Kheifets et al., 2010a). More recent epidemiology studies of childhood leukemia have not materially changed the overall evidence. While the 2010 pooled analysis also showed an association at exposure levels above 0.3 and 0.4μT, the association was weaker than in the previous pooled analyses and statistically not significant. The authors further noted that the association overall was weaker in the most recent studies, but the studies were small and presented no methodological improvements that would assist in the interpretation of the apparent association. Thus, the results of new studies do not alter the previous assessment about the limited epidemiologic evidence.

Several large epidemiologic studies also have been published since the 2010 pooled analysis, but overall provided no new evidence or an explanation for the previously reported association. A French study (Sermage-Faure et al., 2013) reported on residential proximity to high voltage transmission lines and childhood leukemia development using geocoded information on residential addresses of close to 3,000 childhood leukemia cases and 30,000 controls and power line locations across France. Overall no association was observed between childhood leukemia risk and residential proximity to high voltage transmission lines. The authors, however, reported an association in a sub-analysis within 50 m of 225-400 kV lines based on a small number of cases (n=9) that was not statistically significant. Researchers in Denmark (Pedersen et al., 2014) conducted a similar study that included 1,698 childhood leukemia cases and 3,396 healthy control children. The authors reported no statistically significant association between risk and residential proximity to 132 kV, 220 kV, and 400 kV power lines. British epidemiologists

(Bunch et al., 2014) provided an extension and update to a previously published study in the United Kingdom (Draper et al., 2005). The authors extended the study period by 13 years (1962 – 2008), included lower voltage lines (132 kV) in addition to 275/400 kV lines, and included Scotland in addition to England and Wales in their analyses. The updated 2014 study included over 53,000 childhood cancer cases and over 66,000 healthy control children and reported no overall association with residential proximity to 132 kV, 275 kV, and 400 kV power lines for leukemia or for any other cancer among children. The statistical association with distance that was reported in the earlier study (Draper et al., 2005) was not apparent in the extended analysis (Bunch et al., 2014). Italian researchers have published the methods and results of a childhood leukemia case-control study (Magnani et al., 2014; Salvan et al., 2015). The investigators included 412 leukemia cases under the age of 10 years diagnosed in Italy between 1998 and 2001 along with 587 controls and measured (24 – 48 hour) residential exposure to 50Hz magnetic fields in their homes. Overall, no consistent exposure-response pattern was reported by the authors.

Another recent pooled analysis by Schüz and colleagues (Schüz et al., 2012) followed up on suggestions from earlier studies (Foliart et al., 2006, Svendsen et al., 2007) that exposure to ELF magnetic fields may promote growth of leukemia cells and thus affect survival of children diagnosed with leukemia. The Schüz et al. pooled analysis combined data on more than 3,000 cases of childhood leukemia from Canada, Denmark, Germany, Japan, the United Kingdom, and the United States. Based on their results the authors concluded that exposure to ELF magnetic fields had no impact on the survival probability or risk of relapse in children with leukemia.

Several methodological studies also have investigated the possibility of alternative explanations for the reported association. For example, the potential role of selection bias (Slusky et al., 2014; Mezei et al., 2008), residential mobility of the study subjects (Swanson, 2013), and corona ions generated in the vicinity of transmission lines (Swanson et al., 2014) have been investigated. None of these investigations, however, identified factors that would fully explain the observed epidemiologic associations.

Unlike for childhood leukemia, no consistent associations were reported for childhood brain cancer in epidemiologic studies. Both the IARC and WHO assessments concluded that the

evidence for an association with childhood brain cancer is inadequate. Similarly, the DCMNR report also considered the evidence inadequate for all childhood cancers other than leukemia. Results of a meta-analysis (Mezei et al., 2008) and a pooled analysis (Kheifets et al. 2010b) that followed up on the WHO recommendation to jointly analyze childhood brain cancer ELF EMF studies reported no consistent risk increase or exposure-response relationship regardless of the type of exposure metrics, cutpoints, adjustment for confounders, exclusion of particular studies, or analytical methods used.

## Assessment

Results of recent studies are consistent with results of earlier studies and with a weak overall association for childhood leukemia. Methodological investigations have failed to provide convincing support for any single alternative, that is, non-causal, explanation for the reported associations. Some of the more recent and methodologically more advanced studies show weaker associations or no associations between estimates of exposure to ELF EMF and leukemia among children. Assuming that methodological improvements in epidemiologic studies contribute to better estimates of the "true" underlying relationships between exposure and the health outcome under investigation, weaker or no association in more recent studies would suggest that some of the associations reported earlier might be due to bias or other factors, thus, weakening our confidence that the association represents a true relationship. Overall, however, more recent results taken together with previous results do not as yet provide sufficient evidence to alter the earlier conclusions with respect to "limited" evidence based on childhood leukemia epidemiologic studies. The 2015 conclusion of SCENIHR that there remains an unexplained epidemiologic association reported in childhood leukemia studies, which, however, could not be interpreted as causal due to lack of supportive evidence from animal and mechanistic studies, is consistent with previous assessments and does not represent a change compared to the 2007 conclusions of the DCMNR and the WHO.

For other childhood cancers, which mainly include childhood brain cancer, the evidence was judged inadequate by both the DCMNR and WHO reports. Recent studies did not provide new evidence for an association. Particularly, the combined analyses of epidemiologic studies in the meta- and pooled analyses provided no support for an association with childhood brain cancer.

Thus, an association between ELF EMF and childhood brain cancer remains unlikely and not supported by epidemiologic studies. The 2015 SCENIHR report similarly concludes that the evidence for childhood cancers, other than leukemia, show no consistent associations.

# Adult Cancer

## Conclusions of the DCMNR and the WHO in 2007

Adult cancers also have been in the focus of ELF EMF research, particularly leukemia and cancers of the brain and breast. The 2002 carcinogenicity assessment by IARC concluded that the evidence from epidemiologic studies on all adult cancers is inadequate and overall provides no support for a carcinogenic effect of ELF EMF. The 2007 DCMNR concurred with and adopted this assessment. Similarly, the 2007 WHO EHC report confirmed that the evidence from adult cancer epidemiologic studies is inadequate for all adult cancers. In addition, the WHO specifically concluded that the evidence from breast cancer epidemiologic studies does not support an association.

## Key Recent Studies

A meta-analysis of occupational ELF EMF exposure and adult leukemia and brain cancer provided a comprehensive assessment of the available literature in this area (Kheifets et al., 2008). While the study reported a small and statistically significant increase of leukemia and brain cancer in relation to the highest estimates of magnetic-field exposure in the individual studies, several findings led the authors to conclude that magnetic-field exposure is not responsible for the observed associations. The more recent studies, some of them with improved exposure assessment and analytical methods, showed weaker associations than previous studies. There was also a lack of a consistent pattern among subtypes when the previous and more recent studies were compared. The authors concluded that “the lack of a clear pattern of EMF exposure and outcome risk does not support a hypothesis that these exposures are responsible for the observed excess risk” (Kheifets et al., 2008, p. 677).

More recent epidemiologic studies of adult leukemia and brain cancer investigated both occupational and residential exposures. Case-control epidemiologic studies from Brazil

(Marcilio et al., 2011) and the United Kingdom (Elliott et al., 2013) have included residential proximity as a main metric for ELF EMF exposure. The Brazilian study included 1,857 cases of leukemia, 2,357 cases of brain cancer, and 4,706 controls. The United Kingdom study included 7,823 leukemia and 6,781 brain cancer cases along with close to 80,000 controls. Overall, neither of the two studies provided consistent support for an association for either leukemia or brain cancer. The relationship of adult brain cancer and leukemia with occupational exposure to ELF EMF has been assessed in large cohort studies, including the British study of about 70,000 electricity industry workers (Sorahan, 2012; Sorahan, 2014) and the study of about 120,000 adults in the Netherlands (Koeman et al., 2014). A large international case-control study that included more than 5,000 brain cancer cases (Turner et al., 2014) also investigated occupational exposure to ELF EMF. None of these studies reported consistent and convincing associations with either adult leukemia or brain cancer.

In light of the largely unsupportive evidence from breast cancer epidemiologic studies, the 2007 WHO EMF research agenda did not recommend further research on breast cancer, although several epidemiologic studies have continued to investigate the association between ELF EMF exposure and breast cancer. The British case-control study of residential distance to transmission lines (Elliott et al., 2013) also included more than 29,000 cases of female breast cancer and reported no risk increases for breast cancer with either distance to power lines or estimated magnetic-field exposure. The British and Dutch cohort studies also identified breast cancer cases but reported no risk increase for breast cancer with occupational exposure to ELF EMF (Sorahan, 2012; Koeman et al., 2014). Researchers in a large occupational cohort study of about 267,000 Chinese female textile workers identified 1,678 incidence cases of breast cancer diagnosed between 1989 and 2000 (Li et al., 2013). Based on detailed work history of individual workers and a measurement-based job-exposure matrix for ELF EMF, the investigators reported no associations for EMF exposure estimates and breast cancer risk. Several meta-analyses of EMF epidemiologic studies have also been conducted by Chinese scientists for both male and female breast cancers (Chen et al., 2013; Sun et al., 2013; Zhao et al., 2014). These latter two studies reported weak but significant associations with EMF, which are contrary to conclusions of the WHO and other risk assessment panels. This may be explained by the reliance on earlier and methodologically less advanced studies in the meta-analyses.

### Assessment

The epidemiologic literature on adult leukemia and brain cancer that has been published following 2007 has not provided substantive or considerable new evidence that would alter the earlier conclusion of the evidence being inadequate. The meta-analysis indicated that more recent and methodologically more advanced studies tend to indicate weaker associations with EMF, compared to older and less advanced studies, and no consistent pattern has emerged with respect to cancer subtypes when temporal trend was evaluated across studies. Recent case-control and cohort studies either indicated no association or only weak and inconsistent associations for adult leukemia and brain cancer. Overall, the evidence makes it unlikely that these adult cancers are causally linked to ELF EMF.

For breast cancer, the recently published studies add to the growing body of scientific evidence against the causal role of ELF EMF exposure in breast cancer development. These studies, overall, strengthen the conclusion of the WHO that the evidence does not support an association for breast cancer.

The conclusion of the 2015 SCENIHR report stating that, overall, studies on "… adult cancers show no consistent associations" (SCENIHR, 2015, p. 158) is consistent with earlier assessments, including those of the 2007 DCMNR and the WHO reports.

## Adult Non-Cancer Outcomes

### Conclusions of the DCMNR and the WHO in 2007

To date, the 2007 WHO EHC report provides the most comprehensive evaluation of the scientific research regarding potential effects of ELF EMF on non-cancer health outcomes. Overall, the WHO EHC concluded that the evidence was inadequate for all of the investigated non-cancer health outcomes with respect to exposure to ELF electric fields and magnetic fields, and no adverse health effects have been confirmed due to ELF EMF exposure. The specific areas that have been reviewed by the WHO Task Group included the potential effect of neurobehavior and the neuroendocrine system, neurodegenerative and cardiovascular diseases, potential immunological and hematological effects, and potential effects on reproduction and

development. The DCMNR report is consistent with the WHO report, and opines that the "evidence is unconvincing" for any effects on birth outcomes, reproduction and development, on neurodegenerative and cardiovascular diseases, or on the immune and hematological systems (DCMNR, 2007, p. 13).

## Key Recent Studies

Several cohort studies have evaluated cardiovascular disease mortality in association with estimated occupational exposure to ELF EMF. These included a Swiss study of about 20,000 railway workers (Röösli et al., 2008), a cohort study of about 120,000 adults in the Netherlands (Koeman et al., 2013), and an analysis of the National Longitudinal Mortality Study in the United States (Cooper et al., 2009). None of these studies indicate an association with cardiovascular mortality that would support the role of ELF EMF exposure in disease development.

Mortality due to neurodegenerative diseases in relation to occupational exposure to ELF EMF has been investigated among Swiss railway workers (Röösli et al., 2007), among British electricity workers (Sorahan and Kheifets, 2007), and in large general population cohorts in Switzerland (Huss et al., 2014)and the Netherlands (van der Mark et al., 2014). While some of the studies reported risk increases, these studies taken together provide no strong or consistent support for an association between occupational ELF EMF exposure and any of the neurodegenerative disease mortality. Residential exposure to ELF EMF has been investigated in a large Swiss cohort study (Huss et al., 2009). The study reported an increase in Alzheimer's disease mortality among those who lived within 50m of 220 – 380 kV transmission lines compared to those who lived more than 600m away from these lines. A similar study in Denmark that used improved methodology (Frei et al., 2013), however, was not able to replicate the findings reported in the Switzerland study. The Danish study included newly diagnosed cases of neurodegenerative diseases in their analysis, which represent a substantial improvement in methods compared to using death certificates as was done in the Swiss study. A Brazilian mortality study (Marcilio et al., 2011) and a Dutch study of newly diagnosed ALS cases (Seelen et al., 2014) reported no association between residential distance to high-voltage transmission lines and ALS. Some clinic-based case-control studies reported associations between estimated

occupational ELF EMF exposure and Alzheimer's disease or dementia (e.g., Davanipour et al., 2007); the main limitations of these studies are the potential for recall bias and control selection bias. A recent study reported an increase in cognitive dysfunction among Hispanic elderly individuals in the United States in relation to estimated occupational exposure (Davanipour et al., 2014). The study, however, was limited due to its cross-sectional design (which makes it difficult to know if the exposure preceded the disease or vice versa), the lack of clear diagnostic criteria, and the crude assessment of occupational exposures.

A recent meta-analysis of a large number of epidemiologic studies on occupational exposure to magnetic fields and neurodegenerative disease suggested that Alzheimer's disease risk was moderately associated with estimated magnetic-field levels (Vergara et al., 2013). There was a statistical indication, however, of publication bias favoring the publication of positive studies, which the authors concluded may at least partially explain the association for Alzheimer's disease. For ALS, the meta-analysis indicated a moderate risk increase as well, but it was stronger in studies using occupational titles than in studies using estimates of magnetic fields, leading the authors to conclude that exposure to magnetic fields probably does not explain the observed association for ALS. As the reported associations for ALS tended to be with certain occupations rather than estimates of magnetic fields, it has been suggested that electric shocks may be a possible confounder in the association. Recent studies of ALS, however, did not provide convincing evidence for an association with electric shocks (van der Mark et al., 2014; Vergara et al., 2014; Huss et al., 2014).

Adverse pregnancy outcomes and their potential relationship with ELF EMF exposure have continued to be researched in epidemiologic studies. Many of these studies, however, had severe flaws or limitations in their design, case definition, exposure assessment, or reporting that render them little or no weight in an overall weight of evidence evaluation (e.g., Shamsi and Mahmoudabadi, 2013; Mahram and Ghazavi, 2013; Wang et al., 2013; Su et al., 2014). A Canadian study (Auger et al., 2012) investigated occurrence of stillbirth in relation to residential proximity to power lines. Of about half a million births, the authors identified 2,033 stillbirths in Québec and determined the distance between postal code at birth and the nearest power line. No consistent association or trend was reported between stillbirth and residential distance. Reliance

on postal code for address and distance to power lines as proxy of ELF EMF exposure are the main limitations of the study. A British study investigated about 140,000 singleton births between 2004 and 2008 (de Vocht et al., 2014). The authors reported slightly reduced average birth weight (by 212 grams) among women who resided within 50m of a power line; no other clinical birth outcomes were related to residential proximity to power lines.

Two studies from the same investigators have been published that linked asthma and obesity in the offspring to exposure to ELF EMF of the mothers during pregnancy (Li et al., 2011; Li et al., 2012). These findings have not been replicated by other researchers and are difficult to interpret given the lack of a plausible hypothesis, and the potential confounding by socioeconomic status and other known risk factors (Brain et al., 2012; Villeneuve et al., 2012).

## Assessment

Overall, results from more recent studies have not changed the totality of the evidence considerably with respect to non-cancer health outcomes, and the evidence remains inadequate to causally link any of the non-cancer outcomes to ELF EMF exposure. For cardiovascular diseases, the new studies overall reported no associations, which confirmed previous conclusions that cardiovascular diseases are likely not related to ELF EMF exposure. Although a small degree of scientific uncertainty remains with respect to a potential association with Alzheimer's disease and ALS as a result of weak associations reported in some of the studies, the results from more recent studies on neurodegenerative disease are consistent with previous studies and the overall evidence remains inadequate to support a causal relationship. No convincing new evidence emerged from recent studies on reproductive and developmental outcomes and the evidence for these outcomes remains inadequate, as well. Similar to the 2007 DCMNR report, the 2015 SCENIHR report did not identify any health outcomes that are causally related to ELF EMF exposure. For self-reported symptoms and neurodegenerative diseases the evidence is characterized as not convincing, for adverse pregnancy outcomes the SCENIHR report finds "no evidence," the report opines that the studies of childhood health outcomes suggest "implausible" effects as a result of exposure during pregnancy, and no effects are shown in studies of reproductive function in humans (SCENIHR, 2015, p. 7).

# Summary and Conclusions

Contemporary life is unimaginable without electricity, which over the past century has become an integral part of all modern societies. Electricity, wherever it is generated, transmitted, distributed, and used in our homes, businesses, and other locations, is associated with EMF. Electricity in Ireland and Europe is associated with 50 Hz EMF, while in North America and in some other parts of the world it is associated with 60 Hz EMF. Since the late 1970s substantial numbers of scientific research studies have been conducted worldwide. These research studies have evaluated potential cancer and non-cancer health outcomes in children and adults in relation to both residential and occupational exposure to EMF. Scientific research studies in this area can be broadly categorized into epidemiologic studies of humans, laboratory animal studies, and laboratory studies using cells and tissues. Because of the amount and complexity of the scientific studies and the variety of scientific disciplines involved in this area, comprehensive evaluations of the available scientific research results are best done by multi-disciplinary expert panels that include a group of independent scientists with expertise in relevant scientific disciplines. A valid assessment of the scientific literature as to potential health effects involves the identification and evaluation of all relevant scientific peer-reviewed publications. Individual studies are then evaluated as to their relative merit based on their strengths and limitations in a weight-of-evidence assessment. Such expert panels have been assembled by various national and international scientific and government agencies worldwide that conducted a thorough evaluation of the relevant scientific literature. Such evaluations were conducted, among others, by the United States' National Institute of Environmental Health Sciences, the United Kingdom's National Radiological Protection Board, ICNIRP, IARC, and the WHO. None of these agencies has concluded that the evidence overall confirms the existence of any health consequences due to exposure to EMF. While these evaluations and reviews have noted the limited evidence based on statistical associations reported in epidemiologic studies of childhood leukemia, they also noted that the evidence is not supported by the critical laboratory animal studies reporting no effect of exposure and the lack of known biophysical mechanisms to explain a potential carcinogenic effect. Thus, overall, the evidence from childhood leukemia studies are not strong enough to conclude that EMF is a cause or even

probable cause of leukemia and, as concluded by ICNIRP, it is not sufficient to provide a scientific basis for exposure guidelines.

In Ireland, the relevant scientific research has been evaluated and a report on this topic was prepared by a group of four scientists commissioned by DCMNR in 2007. The DCMNR report and the WHO EHC, also published in 2007, have been the main reference documents guiding public policy on ELF EMF in Ireland. The DCMNR report, similar to the WHO EHC, acknowledged the reported association from epidemiologic studies of childhood leukemia, primarily from the pooled analyses conducted by Greenland et al. (2000) and Ahlbom et al. (2000), but stated that this association is not supported by studies in experimental animals. The evidence, the DCMNR report states, is inadequate for all other cancers in children and all cancers in adults. The DCMNR report also states that the evidence is unconvincing for all other non-cancer health outcomes, including adverse birth outcomes, neurodegenerative diseases, and cardiovascular diseases. Since 2007, evaluations have been published by expert panels of national and international organizations, such as ICNIRP, SCENIHR, the Swedish Radiation Protection/Safety Authority, the Canadian FPTRP, and the Ministry of Health of New Zealand. These reviews all reached conclusions consistent with those of the DCMNR report and did not conclude that any adverse health effects in relation to ELF EMF exposure have been established by the accumulated scientific research results.

In 2015, SCENIHR assembled a 12-member scientific working group to update its previous 2009 report and evaluate relevant EMF health research published between 2009 and 2014. The 2015 SCENIHR opinion is consistent with previous SCENIHR opinions issued in 2007 and 2009, and did not conclude that the scientific evidence confirms any adverse health effects. The 2015 SCENIHR review followed similar principles in their methods for review to the methods discussed in the 2007 DCMNR report. The 2015 SCENIHR report also had similar conclusions on specific outcomes, such as childhood leukemia, other cancers in children and adults, and non-cancer health outcomes, such as neurodegenerative diseases. The similarity of the conclusions should not be understood to indicate that no scientific progress had occurred over the 8-year period between the publication of the two reports, although, as noted by SCENIHR, some topics have not been the subject of much research and so the conclusions of the reviews

are necessarily limited. For example, a large Danish registry study of good design (Frei et al., 2013) eclipsed the suggestion from the 2009 SCENIHR report that magnetic-field exposure was associated with Alzheimer's disease, a conclusion that was based on an earlier Swiss cohort study. Such differences, however, are not reflected in the conclusions of DCMNR and SCENIHR reviews due to the conservative nature of the opinions they expressed.

Similarly, while recent large scale epidemiologic studies from France, Great Britain, and Denmark reported no overall associations for childhood leukemia, the associations observed in earlier studies remain unexplained. As an example, the recent extension by Bunch et al. (2014) of the earlier large childhood cancer epidemiologic study in the United Kingdom (Draper et al., 2005) reported that the originally observed association was only present in the period 1962–1989. Analyses of data in the subsequent 19 years showed no association, resulting in no overall association between residential proximity to power lines and childhood leukemia when the study area and study period was extended.

Each panel also addressed topics not covered by the other. Most but not all of these topics were covered in the SCENIHR review that was aimed to be more comprehensive than the DCMNR review that focused more on addressing questions of public concern.

Altogether, the comparison of the DCMNR and SCENIHR reviews shows that, while much additional research has been published over the 8-year period between their publication, the main conclusions of these reviews are quite consistent—the scientific evidence does not establish that ELF EMF at levels found in everyday environments pose a public health or safety threat.

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# Limitations

At the request of EirGrid plc, Exponent reviewed the relevant scientific literature on EMF and health published following 2007 to evaluate whether the newly published scientific data justify revisions to the conclusions expressed in the 2007 DCMNR report. This report summarises work performed to date and presents the findings resulting from that work. In the analysis, we have relied on published scientific research and agency reports. 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 others than the intended users of this report, and any re-use of this report or its findings, conclusions, or recommendations presented herein for other purposes is 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.

# Appendix A

## IARC Classification System

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

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

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

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

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

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

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

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

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

# Appendix B

# WHO Conclusions on Specific Health Outcomes

| Outcome | WHO Conclusions or Recommendations from Environmental Health Criteria 238: Extremely Low Frequency (ELF) Fields |
|---|---|
| Overall conclusions | New human, animal, and in vitro studies published since the 2002 IARC Monograph, 2002 [*sic*] do not change the overall classification of ELF as a possible human carcinogen (p. 347).<br><br>Acute biological effects [i.e., short-term, transient health effects such as a small shock] have been established for exposure to ELF electric and magnetic fields in the frequency range up to 100 kHz that may have adverse consequences on health. Therefore, exposure limits are needed. International guidelines exist that have addressed this issue. Compliance with these guidelines provides adequate protection. Consistent epidemiological evidence suggests that chronic low-intensity ELF magnetic field exposure is associated with an increased risk of childhood leukaemia. However, the evidence for a causal relationship is limited, therefore exposure limits based upon epidemiological evidence are not recommended, but some precautionary measures are warranted (pp. 355-356). |
| Childhood leukemia | Consistent epidemiological evidence suggests that chronic low intensity ELF magnetic field exposure is associated with an increased risk of childhood leukaemia. However, the evidence for a causal relationship is limited, therefore exposure estimates based upon epidemiological evidence are not recommended, but some precautionary measures are warranted (pp. 355-356). |
| Childhood brain cancer | The WHO described the data related to childhood brain cancer as inadequate. They stated:<br><br>As with childhood leukaemia, a pooled analysis of childhood brain cancer studies should be very informative and is therefore recommended. A pooled analysis of this kind can inexpensively provide a greater and improved insight into the existing data, including the possibility of selection bias and, if the studies are sufficiently homogeneous, can offer the best estimate of risk (p. 18). |
| Adult leukemia and brain cancer | In the case of adult brain cancer and leukaemia, the new studies published after the IARC monograph do not change the conclusion that the overall evidence for an association between ELF [EMF] and the risk of these disease remains inadequate (p. 307). |
| Breast cancer | With these [recent] studies, the evidence for an association between ELF magnetic field exposure and the risk of female breast cancer is weakened considerably and does not support an association of this kind (p. 9). |

| Outcome | WHO Conclusions or Recommendations from Environmental Health Criteria 238: Extremely Low Frequency (ELF) Fields |
|---|---|
| Neurodegenerative diseases | Overall, the evidence for the association between ELF exposure and ALS is considered inadequate. The few studies investigating the association between ELF exposure and Alzheimer's disease are inconsistent. However, the higher quality studies that focused on Alzheimer morbidity rather than mortality do not indicate an association. Altogether, the evidence for an association between ELF exposure and Alzheimer's disease is inadequate (p. 206). |
| Reproductive effects | On the whole, epidemiological studies have not shown an association between adverse human reproductive outcomes and maternal or paternal exposure to ELF fields. There is some evidence for increased risk of miscarriage associated with measured maternal magnetic field exposure, but this evidence is inadequate (p. 255). |
| *In vivo* cancer research | 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 (p. 10). |

# Appendix C

# Comparison of DCMNR and SCENIHR

| Topic | DCMNR 2007 | SCENIHR 2015 |
|---|---|---|
| Methods for Conducting Health Assessment | The research is of adequate quality according to the standards currently prevailing in the scientific community.<br><br>The research has been published in internationally peer- reviewed journals, which are of a quality that is generally accepted as adequate in the scientific community.<br><br>The results of the research have proved to be reproducible (for laboratory research) or consistent (for epidemiological research) based on research of the type referred to above, which has been conducted by other independent researchers.<br><br>The outcome of the research has been substantiated by quantitative analysis, which leads to the conclusion that there is a statistically significant relationship between exposure and effect.<br><br>The strength of the effect is related to the strength of the stimulus; i.e. there is a dose-response relationship. This relationship does not always need to be such that the effect increases as the stimulus becomes stronger; it may also signify a resonance effect, i.e. that there is a maximum effect for a particular stimulus and that the effect for a stronger or weaker stimulus is less marked or perhaps even completely absent (p. 20). | Not all identified studies are necessarily included in the Opinion. On the contrary, a main task is to evaluate and assess the articles and the scientific weight that is to be given to each of them (p. 12).<br><br>Detailed criteria for selecting these studies have been published in the SCENIHR Memorandum "Use of the scientific literature for risk assessment purposes – a weight of evidence approach" (SCENIHR 2012). Additional criteria specifically for studies of EMF health effects were also listed in a previous SCENIHR Opinion (SCENIHR 2009). Although anecdotal evidence can be valuable for highlighting an area of concern and thus initiating scientific studies, this kind of evidence has not been considered in the assessments performed in this Opinion (p. 22).<br><br>Over time, many studies have reported biological effects after EMF exposure. However, the description of the exposure is in many cases not sufficient even for scientists with relevant knowledge and the proper equipment to reproduce the experiment. Papers with poor descriptions of the exposure are therefore of little or no value in risk evaluation and do not provide knowledge about modes of actions (p. 22).<br><br>In research on health effects of EMF, the lack of clearly focused hypotheses is accentuated by the lack of an established biological or biophysical mechanism of action. This does not allow the researchers to specify mechanistically the most relevant exposure indices, but commonly several alternative measures of exposure are evaluated (for instance field strength, exposure frequency, cumulative exposure, time since first exposure etc.). In addition, some studies use multiple end-points, which are equally prone to false positive results (p. 25).<br><br>A weight of evidence approach is used to assess the scientific support for a specific outcome. This is based on data from human, animal and mechanistic studies (the primary evidence) along with exposure. For each line of evidence, the overall quality of the studies is taken into account, as well as the relevance of the studies for the issue in question. The weighting also considers if causality is shown or not in the relevant studies (p. 27). |

| Topic | DCMNR 2007 | SCENIHR 2015 |
|---|---|---|
| Childhood cancer | Results of pooled analysis of around twenty epidemiological studies suggest a doubling of the risk of leukaemia for children exposed to average magnetic fields over 0.3 to 0.4 μT. However, because of the limited knowledge of the aetiology of childhood leukaemia, it is possible that some other exposure, (a confounder) may be the cause of this association. At present there is no experimental evidence that supports the view that this relationship is causal (Kheifets et al, 2005). (p. 38) | The previous assessment of the 2009 SCENIHR Opinion on a possible association between long-term exposure to ELF magnetic fields and an increased risk of childhood leukaemia remains valid. A positive association has been observed in multiple studies in different settings at different points in time. Little progress has been made in explaining the finding, neither in terms of a plausible mechanism for a causal relationship with magnetic field nor in identifying alternative explanations (p. 159).<br><br>The new epidemiological studies are consistent with earlier findings of an increased risk of childhood leukaemia with estimated daily average exposures above 0.3 to 0.4 μT. As stated in the previous Opinions, no mechanisms have been identified and no support is existing from experimental studies that could explain these findings, which, together with shortcomings of the epidemiological studies prevent a causal interpretation (p. 164). |
| Breast cancer | … despite a number of research studies there is little or no evidence for an association between ELF magnetic field exposure and an increased risk for breast cancer (IARC, 2002) (p. 13). | Elliott et al. (2013) conducted a register-based case-control study on adult cancers in relation to distance from high-voltage power lines in England and Wales. They compared 7823 leukaemia cases, 6781 brain and central nervous system tumour cases, 9153 malignant melanoma cases, and 29,202 female breast cancer cases with a control group consisting of other cancers (n=79,507). For distances closest to the power lines, ORs ranged from 0.82 (CI: 0.61-1.11) for melanoma to 1.22 (CI: 0.88-1.69) for brain and central nervous system tumours, hence, providing no evidence of an association. They also estimated the magnetic field strength in relation to the power lines, and for calculated fields exceeding 1 μT compared to <0.1 μT, ORs ranged from 0.68 (CI: 0.39- 1.17) for melanoma to 1.08 (CI: 0.77-1.51) for female breast cancer, again showing no evidence of any association (p. 158). |
| Nervous system disease | The evidence is unconvincing that ELF [**EMF**] is a cause of … Alzheimer's disease, motor neuron disease, suicide and depression, or cardiovascular disease (p. 13). | Only few [*sic*] new studies have been published since the previous Opinion. Although the new studies in some cases have methodological weaknesses, they do not provide support for the previous conclusion that ELF MF exposure increases the risk for Alzheimer´s disease (p. 166). |
| Reproductive function | The evidence is unconvincing that ELF [**EMF**] is a cause of adverse birth outcomes in humans…. There is very weak evidence that maternal or paternal occupational exposure to ELF [**EMF**] causes reproductive effects (p. 13) | In conclusion, recent results do not show an effect of the ELF fields on the reproductive function in humans (p. 185). |

| Topic | DCMNR 2007 | SCENIHR 2015 |
|---|---|---|
| Electromagnetic hypersensitivity and symptoms | No studies have established that EMF exposure leads to the subjective symptoms reported by EHS individuals. Several studies have shown that while the symptoms reported by EHS sufferers are real, they are not linked to EMF exposure. EHS sufferers do not experience worse symptoms when exposed to EMF fields (p. 18). | Overall, existing studies do not provide convincing evidence for a causal relationship between ELF MF exposure and self-reported symptoms (p. 187). |
| Precautionary measures | As a precautionary measure future power lines and power installations should be sited away from heavily populated areas to keep exposures to people low. The evidence for 50 Hz magnetic fields causing childhood leukaemia is too weak to require re-routing of existing lines, and so these measures should only apply to new lines (p. 3).<br><br>There is no doubt that the prudent use of precautionary measures would help reassure many in Ireland who are concerned over EMF exposure (p. 23). | The Council Recommendation also invites the Commission to "keep the matters covered by this recommendation under review, with a view to its revision and updating, taking into account possible effects, which are currently the object of research, including relevant aspects of precaution". (p. 18).<br><br>**Other than endorsing the use of the 1998 ICNIRP exposure guidelines, (http://europa.eu.int/comm/food/fs/sc/ssc/index_en.html) risk assessments of EMF by the committees assembled by the European Commission have not made any recommendations regarding precautionary measures.** |
| In vivo studies (cancer) | In addition, studies were conducted on laboratory animals, mainly rats and mice, exposed for their lifetime to fields up to a thousand times stronger than those experienced by the general public. … laboratory studies do not provide convincing evidence for a causal relationship [**between childhood leukemia and EMF**] so the impact on public health is uncertain (p. 13). | Previously 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 (p. 161). |
| In vivo studies (brain/behavior) | | Largely consistent with earlier results, recent studies have reported that exposure to ELF magnetic fields has no effect on activity or locomotion. There is some evidence from animal studies that exposure to ELF MF may affect the performance of spatial memory tasks (both deficits and improvements have been reported) and engender subtle increases in behavioural anxiety and stress. Other studies have investigated potential molecular and cellular mechanisms, and despite a number of studies continue [*sic*] to report candidate mechanisms, particularly regarding effects on reactive oxygen species, none has been firmly identified that operates at exposure levels found in the everyday environment. Several studies have tried to reveal subtle effects of magnetic fields through their interactions with drugs or other interventions but these have not produced any compelling evidence of field-induced changes on nervous system (p. 178). |

| Topic | DCMNR 2007 | SCENIHR 2015 |
|---|---|---|
| In vitro studies (cancer) | | As concluded in the previous SCENIHR Opinion, data suggest that ELF MF may induce both genotoxic and other biological effects in vitro at flux densities of 100 μT and higher. The mechanisms are not established and the relevance for a connection between ELF MF exposure and childhood leukaemia is unclear. (p. 164) |
| Acute neurostimulation | Acute effects, as discussed below, have been established for exposure to ELF electric and magnetic fields in the frequency range up to 100 kHz. Since these may lead to health hazards, exposure limits are needed. International guidelines (ICNIRP, 1998; IEEE, 2004) exist that have addressed this issue. Observing these guidelines provides adequate protection against established acute effects (p. 13). | |
| Exposure to fields with multiple frequencies | | The few available studies on combined exposure to different EMFs do not provide sufficient evidence for risk assessment (p. 204). |
| Co-exposure with stressors (chemicals) | | … due to the small number of investigations available and the large variety of protocols adopted (different chemical or physical treatments and different EMF exposure conditions), it is not possible to draw concrete conclusions (p. 209). |

# Appendix D

# ICNIRP Guidelines for 50 Hz Electric and Magnetic Fields

**ICNIRP Reference Levels for Exposure to 50 Hz Electric and Magnetic Fields**

| | Electric Fields | Magnetic Fields |
|---|---|---|
| General Public Exposure | 5 kV/m | 2,000 mG |
| Occupational Exposure | 10 kV/m | 10,000 mG |

*Source: ICNIRP, 2010*

# Appendix E

# Key Epidemiologic ELF EMF Studies and Related Papers Published 2007 - 2015

**Childhood Leukemia**

| Author | Year | Study Title |
|---|---|---|
| Abdul Rahman et al. | 2008 | A case-control study on the association between environmental factors and the occurrence of acute leukemia among children in Klang Valley, Malaysia |
| Bunch et al.* | 2014 | Residential distance at birth from overhead high-voltage powerlines: childhood cancer risk in Britain 1962-2008. |
| Calvente et al. | 2010 | Exposure to electromagnetic fields (non-ionizing radiation) and its relationship with childhood leukemia: a systematic review |
| Chang et al. | 2014 | Validity of geographically modeled environmental exposure estimates |
| Does et al. | 2011 | Exposure to electrical contact currents and the risk of childhood leukemia |
| Feizi and Arabi | 2007 | Acute childhood leukemias and exposure to magnetic fields generated by high voltage overhead power lines – a risk factor in Iran |
| Foliart et al. | 2007 | Magnetic field exposure and prognostic factors in childhood leukemia |
| Grellier et al. | 2014 | Potential health impacts of residential exposures to extremely low frequency magnetic fields in Europe |
| Hug et al. | 2010 | Parental occupational exposure to extremely low frequency magnetic fields and childhood cancer: a German case-control study |
| Jirik et al. | 2011 | Assessment of population exposure to extremely low frequency magnetic fields and its possible childhood health risk in the Czech Republic |
| Jirik et al. | 2012 | Association between childhood leukaemia and exposure to power-frequency magnetic fields in middle Europe |
| Kavet et al. | 2011 | The relationship between residential magnetic fields and contact voltage: a pooled analysis |
| Keegan et al. | 2012 | Case–control study of paternal occupation and childhood leukaemia in Great Britain, 1962–2006 |
| Kheifets and Oksuzyan | 2008 | Exposure assessment and other challenges in non-ionizing radiation studies of childhood leukaemia |
| Kheifets et al. | 2010a | Pooled analysis of recent studies on magnetic fields and childhood leukaemia |
| Kheifets et al. | 2011 | Exploring exposure-response for magnetic fields and childhood leukemia |
| Kroll et al. | 2010 | Childhood cancer and magnetic fields from high-voltage power lines in England and Wales: a case-control study |
| Magnani et al. | 2014 | SETIL: Italian multicentric epidemiological case-control study on risk factors for childhood leukaemia, non hodgkin lymphoma and neuroblastoma: study population and prevalence of risk factors in Italy |
| Malagoli et al. | 2010 | Risk of hematological malignancies associated with magnetic fields exposure from power lines: a case control study in two municipalities in northern Italy |
| Maslanyj et al. | 2009 | Power frequency magnetic fields and risk of childhood leukaemia: Misclassification of exposure from the use of the 'distance from power line' exposure surrogate |

**Childhood Leukemia**

| Author | Year | Study Title |
|---|---|---|
| Maslanyj et al. | 2010 | A precautionary public health protection strategy for the possible risk of childhood leukaemia from exposure to power frequency magnetic fields |
| Mejia-Arangure et al. | 2007 | Magnetic fields and acute leukemia in children with Down syndrome |
| Mezei et al. | 2008a | Assessment of selection bias in the Canadian case-control study of residential magnetic field exposure and childhood leukemia |
| Mezei et al. | 2014 | Epidemiology of childhood leukemia in the presence and absence of Down syndrome |
| Pearce et al. | 2007 | Paternal occupational exposure to electro-magnetic fields as a risk factor for cancer in children and young adults: A case-control study from the North of England |
| Pedersen et al. | 2014 | Distance from residence to power line and risk of childhood leukemia: a population-based case-control study in Denmark |
| Pedersen et al. | 2014 | Distance to high-voltage power lines and risk of childhood leukemia - an analysis of confounding by and interaction with other potential risk factors. |
| Pelissari et al. | 2009 | Magnetic fields and acute lymphoblastic leukemia in children: a systematic review of case-control studies |
| Reid et al. | 2011 | Risk of childhood lymphoblastic leukaemia following parental occupational exposure to extremely low frequency electromagnetic fields |
| Repacholi | 2012 | Concern that “EMF” magnetic fields from power lines cause cancer |
| Salvan et al. | 2015 | Childhood leukemia and 50 Hz magnetic fields: findings from the Italian SETIL case-control study |
| Schmiedel and Blettner | 2010 | The association between extremely low-frequency electromagnetic fields and childhood leukaemia in epidemiology: enough is enough? |
| Schüz et al. | 2007 | Nighttime exposure to electromagnetic fields and childhood leukemia: An extended pooled analysis |
| Schüz et al. | 2008 | Exposure to electromagnetic fields and the risk of childhood leukemia: A review |
| Schüz | 2011 | Exposure to extremely low-frequency magnetic fields and the risk of childhood cancer: update of the epidemiological evidence |
| Schüz et al. | 2012 | Extremely low-frequency magnetic fields and survival from childhood acute lymphoblastic leukemia: an international follow-up study |
| Sermage-Faure et al.† | 2013 | Childhood leukaemia close to high-voltage power lines – the Geocap study, 2002–2007 |
| Slusky et al. | 2014 | Potential role of selection bias in the association between childhood leukemia and residential magnetic fields exposure: a population-based assessment |
| Sohrabi et al. | 2010 | Living near overhead high voltage transmission power lines as a risk factor for childhood acute lymphoblastic leukemia: a case-control study |
| Svendsen et al. | 2007 | Exposure to magnetic fields and survival after diagnosis of childhood leukemia: An extended pooled analysis |

**Childhood Leukemia**

| Author | Year | Study Title |
|---|---|---|
| Swanson | 2013 | Residential mobility of populations near UK power lines and implications for childhood leukaemia |
| Swanson and Kheifets | 2012 | Could the geomagnetic field be an effect modifier for studies of power-frequency magnetic fields and childhood leukaemia? |
| Swanson et al. | 2014a | Relative accuracy of grid references derived from postcode and address in UK epidemiological studies of overhead power lines |
| Swanson et al | 2014b | Childhood cancer and exposure to corona ions from power lines: an epidemiological test |
| Teepen and van Dijck | 2012 | Impact of high electromagnetic field levels on childhood leukemia incidence |
| Urayama et al. | 2009 | Factors associated with residential mobility in children with leukemia: Implications for assigning exposures |
| Valera et al | 2014 | Electromagnetic fields at extremely low frequencies and the risk for childhood leukemia: do we have enough information to warrant this association? |
| Wünsch-Filho et al. | 2011 | Exposure to magnetic fields and acute lymphocytic leukemia in São Paulo, Brazil |
| Zhao et al. | 2014a | Magnetic fields exposure and childhood leukemia risk: a meta-analysis based on 11,699 cases and 13,194 controls |
| Ziegelberger et al. | 2011 | Review. Childhood leukemia: Risk factors and the need for an interdisciplinary research agenda |
| †**Comment on Bunch et al.:** | | |
| Jeffers | 2014 | Comment on 'Residential distance at birth from overhead high-voltage powerlines: childhood cancer risk in Britain 1962-2008' |
| ***Comments and Replies on Sermage-Faure et al.:** | | |
| Bonnet-Belfais et al. | 2013 | Comment: childhood leukaemia and power lines--the Geocap study: is proximity an appropriate MF exposure surrogate? |
| Magana Torres and Garcia | 2013 | Comment on 'Childhood leukaemia close to high-voltage power lines--the Geocap study, 2002-2007'--odds ratio and confidence interval. |
| Clavel and Hemon | 2013 | Reply: Comment on 'Childhood leukaemia close to high-voltage power lines--the Geocap study, 2002-2007'--odds ratio and confidence interval |
| Clavel et al. | 2013 | Reply: comment on 'Childhood leukaemia close to high-voltage power lines--the Geocap study, 2002-2007'--is proximity an appropriate MF exposure surrogate? |

**Childhood Brain Cancer**

| Authors | Year | Study |
|---|---|---|
| Bunch et al.* | 2014 | Residential distance at birth from overhead high-voltage powerlines: childhood cancer risk in Britain 1962-2008. |
| Hug et al. | 2010 | Parental occupational exposure to extremely low frequency magnetic fields and childhood cancer: a German case-control study |
| Jirik et al. | 2011 | Assessment of population exposure to extremely low frequency magnetic fields and its possible childhood health risk in the Czech Republic |
| Kheifets et al.† | 2010b | A pooled analysis of extremely low-frequency magnetic fields and childhood brain tumors |
| Kroll et al. | 2010 | Childhood cancer and magnetic fields from high-voltage power lines in England and Wales: A case-control study |
| Li et al. | 2009 | Maternal occupational exposure to extremely low frequency magnetic fields and the risk of brain cancer in the offspring |
| Mezei et al. | 2008b | Residential magnetic field exposure and childhood brain cancer: a meta-analysis |
| Saito et al. | 2010 | Power-frequency magnetic fields and childhood brain tumors: a case-control study in Japan |
| Schüz | 2011 | Exposure to extremely low-frequency magnetic fields and the risk of childhood cancer: update of the epidemiological evidence |
| Swanson et al | 2014b | Childhood cancer and exposure to corona ions from power lines: an epidemiological test |
| ***Comment on Bunch et al.:** | | |
| Jeffers | 2014 | Comment on 'Residential distance at birth from overhead high-voltage powerlines: childhood cancer risk in Britain 1962-2008' |
| **†Comment on Kheifets et al.** | | |
| Milham | 2011 | Re: "A pooled analysis of extremely low-frequency magnetic fields and childhood brain tumors" |

**Adult Leukemia / Lymphoma**

| Authors | Year | Study |
|---|---|---|
| Dominici et al. | 2011 | Genotoxic hazard evaluation in welders occupationally exposed to extremely low-frequency magnetic fields (ELF-MF) |
| Elliott et al.* | 2013 | Adult cancers near high-voltage overhead power lines |
| Johansen et al. | 2007 | Risk for leukaemia and brain and breast cancer among Danish utility workers: A second follow up |
| Karipidis et al. | 2007a | Occupational exposure to power frequency magnetic fields and risk of non-Hodgkin lymphoma. |
| Kaufman et al. | 2009 | Risk factors for leukemia in Thailand |
| Kheifets et al. | 2008 | Occupational electromagnetic fields and leukemia and brain cancer: An update to two meta-analyses |
| Koeman et al. | 2014 | Occupational extremely low-frequency magnetic field exposure and selected cancer outcomes in a prospective Dutch cohort |
| Lowenthal et al. | 2007 | Residential exposure to electric power transmission lines and risk of lymphoproliferative and myeloproliferative disorders: A case-control study |
| Marcilio et al. | 2011 | Adult mortality from leukemia, brain cancer, amyotrophic lateral sclerosis and magnetic fields from power lines: a case-control study in Brazil |
| Richardson et al. | 2008 | Occupational risk factors for non-Hodgkin's lymphoma: A population-based case-control study in northern Germany |
| Rodriguez-Garcia and Ramos | 2012 | High incidence of acute leukemia in the proximity of some industrial facilities in El Bierzo, northwestern Spain |
| Röösli et al. | 2007a | Leukaemia, brain tumors and exposure to extremely low frequency magnetic fields: Cohort study of Swiss railway employees |
| Sorahan | 2012 | Cancer incidence in UK electricity generation and transmission workers, 1973–2008 |
| Wong et al. | 2010 | A hospital-based case-control study of non-Hodgkin lymphoid neoplasms in Shanghai: Analysis of personal characteristics, lifestyle, and environmental risk factors by subtypes of the WHO classification |
| ***Comment and Replies on Elliot et al.:** | | |
| Elliott and Toledano | 2013 | Rejoinder: adult cancers and magnetic fields from overhead power lines: epidemiologic investigation, not speculation |
| Philips et al. | 2013 | Letter to the Editor: Adult cancers near high-voltage power lines |
| De Vocht | 2013 | Letter to the Editor: Adult cancers near high-voltage power lines |
| Schüz | 2013 | Commentary: power lines and cancer in adults: settling a long-standing debate? |

**Adult Brain Cancer**

| Authors | Year | Study |
|---|---|---|
| Baldi et al.* | 2011 | Occupational and residential exposure to electromagnetic fields and risk of brain tumors in adults: A case-control study in Gironde, France |
| Coble et al. | 2009 | Occupational exposure to magnetic fields and the risk of brain tumors |
| Elliott et al.† | 2013 | Adult cancers near high-voltage overhead power lines |

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|---|---|---|
| Gomes et al | 2011 | Occupational and environmental risk factors of adult primary brain cancers: a systematic review |
| Johansen et al. | 2007 | Risk for leukaemia and brain and breast cancer among Danish utility workers: A second follow up |
| Karipidis et al. | 2007b | Occupational exposure to low frequency magnetic fields and the risk of low grade and high grade glioma |
| Kheifets et al. | 2008 | Occupational electromagnetic fields and leukemia and brain cancer: An update to two meta-analyses |
| Koeman et al. | 2014 | Occupational extremely low-frequency magnetic field exposure and selected cancer outcomes in a prospective Dutch cohort |
| Marcilio et al. | 2011 | Adult mortality from leukemia, brain cancer, amyotrophic lateral sclerosis and magnetic fields from power lines: a case-control study in Brazil |
| Röösli et al. | 2007b | Leukaemia, brain tumors and exposure to extremely low frequency magnetic fields: Cohort study of Swiss railway employees |
| Sorahan | 2012 | Cancer incidence in UK electricity generation and transmission workers, 1973–2008 |
| Sorahan | 2014 | Magnetic fields and brain tumour risks in UK electricity supply workers |
| Turner et al. | 2014 | Occupational exposure to extremely low frequency magnetic fields and brain tumour risks in the INTEROCC study |
| ***Author's reply to Baldi et al.:** | | |
| Morgan | 2012 | Author's reply to: Occupational and residential exposure to electromagnetic fields and risk of brain tumours in adults: a case-control study in Gironde, France. |
| †**Comment and authors' reply to Elliot et al.:** | | |
| Elliott and Toledano | 2013 | Rejoinder: adult cancers and magnetic fields from overhead power lines: epidemiologic investigation, not speculation |
| Philips et al. | 2013 | Letter to the Editor: Adult cancers near high-voltage power lines |
| De Vocht | 2013 | Letter to the Editor: Adult cancers near high-voltage power lines |
| Schüz | 2013 | Commentary: power lines and cancer in adults: settling a long-standing debate? |

**Breast Cancer**

| Authors | Year | Study |
|---|---|---|
| Chen et al. | 2010 | Extremely low-frequency electromagnetic fields exposure and female breast cancer risk: a meta-analysis based on 24,338 cases and 60,628 controls. |
| Chen et al. | 2013 | A meta-analysis on the relationship between exposure to ELF-EMFs and the risk of female breast cancer |
| Davanipour and Sobel | 2009 | Long-term exposure to magnetic fields and the risks of Alzheimer's disease and breast cancer: Further biological research. |
| Davis and Mirick | 2007 | Residential magnetic fields, medication use, and the risk of breast cancer. |
| Elliott et al.* | 2013 | Adult cancers near high-voltage overhead power lines |
| Feytching | 2013 | Invited commentary: extremely low-frequency magnetic fields and breast cancer--now it is enough! |
| Hulka and Moorman | 2008 | Breast cancer: hormones and other risk factors |
| Johansen et al. | 2007 | Risk for leukaemia and brain and breast cancer among Danish utility workers: A second follow-up. |
| Koeman et al. | 2014 | Occupational extremely low-frequency magnetic field exposure and selected cancer outcomes in a prospective Dutch cohort |
| Li et al | 2013 | Occupational exposure to magnetic fields and breast cancer among women textile workers in Shanghai, China |
| McElroy et al. | 2007 | Occupational exposure to electromagnetic field and breast cancer risk in a large, population-based, case-control study in the United States. |
| Milham and Ossiander | 2007 | Electric typewriter exposure and increased female breast cancer mortality in typists |
| Peplonska et al. | 2007 | Occupation and breast cancer risk in Polish women: a population-based case-control study |
| Ray et al. | 2007 | Occupational exposures and breast cancer among women textile workers in Shanghai. |
| Sorahan | 2012 | Cancer incidence in UK electricity generation and transmission workers, 1973–2008 |
| Sun et al. | 2013 | Electromagnetic field exposure and male breast cancer risk: a meta-analysis of 18 studies |
| Zhao et al. | 2014b | Relationship between exposure to extremely low-frequency electromagnetic fields and breast cancer risk: a meta-analysis. |
| ***Comment and Replies on Elliot et al.** | | |
| Philips et al. | 2013 | Letter to the Editor: Adult cancers near high-voltage power lines |
| De Vocht | 2013 | Letter to the Editor: Adult cancers near high-voltage power lines |
| Schüz | 2013 | Commentary: power lines and cancer in adults: settling a long-standing debate? |

**Neurodegenerative Disease**

| Authors | Year | Study |
|---|---|---|
| Andel et al. | 2010 | Work-related exposure to extremely low-frequency magnetic fields and dementia: Results from the population-based study of dementia in Swedish twins. |
| Barth et al. | 2010 | Effects of extremely low frequency magnetic field exposure on cognitive functions: results of a meta-analysis |
| Brouwer et al. | 2015 | Occupational exposures and Parkinson's disease mortality in a prospective Dutch cohort |
| Capozzela et al. | 2014 | Work related etiology of amyotrophic lateral sclerosis (ALS): a meta-analysis |
| Das et al. | 2012 | Familial, environmental, and occupational risk factors in development of amyotrophic lateral sclerosis |
| Davanipour et al. | 2007 | A case-control study of occupational magnetic field exposure and Alzheimer's disease: results from the California Alzheimer's Disease Diagnosis and Treatment Centers. |
| Davanipour and Sobel | 2009 | Long-term exposure to magnetic fields and the risks of Alzheimer's disease and breast cancer: Further biological research. |
| Davanipour et al | 2014 | Severe Cognitive Dysfunction and Occupational Extremely Low Frequency Magnetic Field Exposure among Elderly Mexican Americans |
| Frei et al. | 2013 | Residential distance to high-voltage power lines and risk of neurodegenerative diseases: a Danish population-based case-control study |
| García, et al. | 2008 | Occupational exposure to extremely low frequency electric and magnetic fields and Alzheimer disease: a meta-analysis. |
| Grell et al. | 2012 | Risk of neurological diseases among survivors of electric shocks: a nationwide cohort study, Denmark, 1968-2008 |
| Huss, et al. | 2009 | Residence near power lines and mortality from neurodegenerative diseases: longitudinal study of the Swiss population. |
| Huss et al. | 2015 | Occupational exposure to magnetic fields and electric shocks and risk of ALS: The Swiss National Cohort |
| Ingre et al | 2015 | Risk factors for amyotrophic lateral sclerosis |
| Jiang et al. | 2013 | Epidemiology and etiology of Alzheimer's disease: from genetic to non-genetic factors |
| Maes and Verschaeve | 2012 | Can cytogenetics explain the possible association between exposure to extreme low-frequency magnetic fields and Alzheimer's disease? |
| Marcilio et al. | 2011 | Adult mortality from leukemia, brain cancer, amyotrophic lateral sclerosis and magnetic fields from power lines: a case-control study in Brazil |
| Parlett et al. | 2011 | Evaluation of occupational exposure to magnetic fields and motor neuron disease mortality in a population-based cohort |
| Röösli, et al. | 2007b | Mortality from neurodegenerative disease and exposure to extremely low-frequency magnetic fields: 31 years of observations on Swiss railway employees |
| Santibáñez, et al. | 2007 | Occupational risk factors in Alzheimer's disease: A review assessing the quality of published epidemiological studies |

**Neurodegenerative Disease**

| Authors | Year | Study |
|---|---|---|
| Seelen et al. | 2014 | Residential exposure to extremely low frequency electromagnetic fields and the risk of ALS |
| Seidler et al. | 2007 | Occupational exposure to low frequency magnetic fields and dementia: a case-control study. |
| Sorahan and Kheifets | 2007 | Mortality from Alzheimer's, motor neurone and Parkinson's disease in relation to magnetic field exposure: findings from the study of UK electricity generation and transmission workers, 1973-2004. |
| Sorahan and Mohammed | 2014 | Neurodegenerative disease and magnetic field exposure in UK electricity supply workers |
| Trojsi et al | 2013 | Exposure to environmental toxicants and pathogenesis of amyotrophic lateral sclerosis: state of the art and research perspectives |
| Van der Mark et al. | 2014 | Extremely low-frequency magnetic field exposure, electrical shocks and risk of Parkinson's disease |
| Vergara et al. | 2013 | Occupational exposure to extremely low-frequency magnetic fields and neurodegenerative disease: A meta-analysis |
| Vergara et al. | 2015 | Case-control study of occupational exposure to electric shocks and magnetic fields and mortality from amyotrophic lateral sclerosis in the US 1991-1999 |
| Vinceti et al. | 2012 | Environmental risk factors for amyotrophic lateral sclerosis: methodological issues in epidemiologic studies |
| Wirdefeldt et al. | 2011 | Epidemiology and etiology of Parkinson’s disease: a review of the evidence |
| Zhou et al. | 2012 | Association between extremely low-frequency electromagnetic fields occupations and amyotrophic lateral sclerosis: A meta-analysis |

**Reproductive and Developmental Effects**

| Authors | Year | Study |
|---|---|---|
| Auger et al. | 2011 | The relationship between residential proximity to extremely low frequency power transmission lines and adverse birth outcomes. |
| Auger et al. | 2012 | Stillbirth and residential proximity to extremely low frequency power transmission lines: a retrospective cohort study |
| Bellieni et al | 2008 | Electromagnetic fields produced by incubators influence heart rate variability in newborns |
| Bellieni et al. | 2012 | Is newborn melatonin production influenced by magnetic fields produced by incubators? |
| Brain et al | 2012 | Observations of power-line magnetic fields associated with asthma in children |
| de Vocht et al. | 2014 | Maternal residential proximity to sources of extremely low frequency electromagnetic fields and adverse birth outcomes in a UK cohort |
| De Fleurian et al. | 2009 | Occupational exposures obtained by questionnaire in clinical practice and their association with semen quality |
| Gye and Park | 2012 | Effect of electromagnetic field exposure on the reproductive system |
| Lewis et al | 2015 | Temporal variability of daily personal magnetic field exposure metrics in pregnant women |
| Li et al. | 2010 | Exposure to magnetic fields and the risk of poor sperm quality |
| Li et al. | 2011 | Maternal exposure to magnetic fields during pregnancy in relation to the risk of asthma in offspring |
| Li et al. | 2012 | A prospective study of in-utero exposure to magnetic fields and the risk of childhood obesity |
| Mahram and Ghazavi | 2013 | The effect of extremely low frequency electromagnetic fields on pregnancy and fetal growth, and development |
| Malagoli et al. | 2012 | Maternal exposure to magnetic fields from high-voltage power lines and the risk of birth defects |
| Mortazavi et al. | 2013 | The study of the effects of ionizing and non-ionizing radiations on birth weight of newborns to exposed mothers |
| Shamsi Mahmoudabadi et al. | 2013 | Exposure to Extremely Low Frequency Electromagnetic Fields during Pregnancy and the Risk of Spontaneous Abortion: A Case-Control Study |
| Su et al | 2014 | Correlation between exposure to magnetic fields and embryonic development in the first trimester |
| Villeneuve | 2012 | Exposure to magnetic fields during pregnancy and asthma in offspring |
| Wang et al. | 2013 | Residential exposure to 50 Hz magnetic fields and the association with miscarriage risk: a 2-year prospective cohort study |

**Cardiovascular Disease**

| Authors | Year | Study title |
|---|---|---|
| Cooper et al. | 2009 | A population-based cohort study of occupational exposure to magnetic fields and cardiovascular disease mortality. |
| Elmas | 2013 | Effects of electromagnetic field exposure on the heart: a systematic review |
| Koeman et al. | 2013 | Occupational exposure to extremely low-frequency magnetic fields and cardiovascular disease mortality in a prospective cohort study |
| Liu et al. | 2013 | Effects of extremely low frequency electromagnetic field on the health of workers in automotive industry |
| Röösli et al | 2008 | Cardiovascular mortality and exposure to extremely low frequency magnetic fields: a cohort study of Swiss railway workers. |