Appendix F

Electric and Magnetic Fields Research on Health Effects

Health Sciences

Exponent®

Research on Extremely Low Frequency Electric and Magnetic Fields and Health

Research on Extremely Low Frequency Electric and Magnetic Fields and Health

Prepared for:

The Bonneville Power Administration

Prepared by:

Exponent
420 Lexington Avenue, Suite 1740
New York, NY 10170

January 2011

1003741.000 A0T1 0111 LE02

Contents

List of Figures

List of Tables

Acronyms and Abbreviations

AC	Alternating current
ACGIH	American Conference of Governmental Industrial Hygienists
ALL	Acute lymphoblastic leukemia
AML	Acute myeloid leukemia
BNU	n-butylnitrosourea
BPA	Bonneville Power Administration
CI	Confidence interval
DMBA	7,12-dimethylbenz[a]anthracene
G	Gauss
ELF	Extremely low frequency
EMF	Electric and magnetic fields
EMI	Electromagnetic interference
ENU	ethylnitrosourea
EPRI	Electric Power Research Institute
HR	Hazard ratio
Hz	Hertz
IARC	International Agency for Research on Cancer
ICD	Implanted cardiac device
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IGF-1	Insulin-like growth factor 1
m	Meter
mG	Milligauss
MPD	Myeloproliferative disorder
NIEHS	National Institute of Environmental Health Sciences
NHL	Non-Hodgkin's lymphoma
NK	Natural killer
OR	Odds Ratio
ROW	Right-of-way
RR	Relative risk
SCENIHR	Scientific Committee on Emerging and Newly Identified Health Risks

SES	Socioeconomic status
SSI	Swedish Radiation Protection Authority
TWA	Time-weighted average
WHO	World Health Organization

Introduction

Electrical objects produce two field types—electric fields and magnetic fields. The term field is used to describe the way an object influences its surrounding area. A temperature field, for example, surrounds a warm object, such as a space heater or campfire. Electric and magnetic fields (EMF) surround any object that generates, transmits, or uses electricity, including appliances, electrical wiring, office equipment, generators, and any other electrical devices. These fields are invisible, and they cannot be felt or heard.

Electric fields occur as a result of the electric potential (i.e., voltage) on these objects, and **magnetic fields** occur as a result of current flow through these objects.[1] Just like a temperature field, both electric fields and magnetic fields can be measured, and their levels depend on the properties of the source of the field (e.g., voltage, current, and configuration) and the distance from the source of the field, among other things.

Both electric fields and magnetic fields decrease rapidly with distance from the source, such that a magnetic field of 300 milligauss (mG) within 6 inches of a vacuum cleaner diminishes to 1 mG at 4 feet (NIEHS, 2002). This is similar to the way that the heat generated by a space heater or a campfire lessens as a person moves farther away from it. Although ordinary objects do not block magnetic fields, objects such as trees and buildings easily block electric fields.

The electrical power system in the United States produces alternating current (AC) EMF that changes direction and intensity 60 times per second—i.e., a frequency of 60 Hertz (Hz).[2] This frequency is in the extremely low frequency (ELF) range of the electromagnetic spectrum. Electricity produced by generating stations flows as 60-Hz current through transmission and distribution lines and provides power to the many appliances and electrical devices that we use in our homes, schools, and workplaces. Magnetic fields are found throughout our environment

[1] The electric field is expressed in measurement units of volts per meter (V/m) or kilovolts per meter (kV/m); 1 kilovolt per meter is equal to 1,000 V/m. The strength of magnetic fields is expressed as magnetic flux density in units called gauss (G), or in milligauss (mG), where 1 G is equal to 1,000 mG.

[2] Europe's electrical system produces 50-Hz EMF. Since 50-Hz EMF is also in the ELF range, research on 50-Hz EMF is relevant to questions on 60-Hz EMF.

because electricity is needed for so many things in our daily lives, from lighting, heating, and cooling our homes to powering our refrigerators and computers.

Questions about whether these ubiquitous exposures could affect our health began to be raised in the 1970s. Since then, researchers from many different scientific disciplines have investigated this question, and hundreds of studies have been conducted. The public frequently expresses concern about ELF EMF, particularly in the context of new transmission lines. The intent of this report is to describe what this large body of research has told us about ELF EMF and the precautions, if any, recommended by public health agencies

In July 2007, Exponent provided a report to the Bonneville Power Administration (BPA) that described the conclusions of a comprehensive, weight-of-evidence review published by the World Health Organization (WHO) in June 2007; the portion of Exponent's 2007 report that describes the conclusions of the WHO report is attached as Appendix 1 for reference.[3] The WHO review still represents the most recent comprehensive review of the literature by a multidisciplinary scientific panel. The WHO organized a multidisciplinary Task Group of 21 scientists from around the world to draft a Monograph that summarized the research and provided conclusions as to whether there are risks associated with ELF EMF and, if so, at what exposure levels (WHO, 2007a). The report concluded that the only established effects of ELF EMF exposure are acute neurostimulatory effects (i.e., shock-like effects) that occur at very high levels of exposure; these exposure levels are not encountered in ordinary residential or occupational environments. The fact sheet from the WHO review is attached as Appendix 2 (WHO, 2007b) and can be found at http://www.who.int/mediacentre/factsheets/fs322/en/print.html.

Research is a constantly evolving process. Despite the volume of research available on ELF EMF and the large reduction in uncertainty that research has achieved over the years, scientists continue research in this area with the goal of clarifying and replicating old findings and testing new hypotheses. New studies on ELF EMF are published every month. While the WHO review provides a comprehensive and relatively up-to-date summary of the status of research on

[3] Exponent. Assessment of Research Regarding EMF and Health and Environmental Effects. Olympic Peninsula Reinforcement Transmission Line Project. July 2007.

this topic, new research has the potential to modify or strengthen conclusions. The BPA has, therefore, requested an update on the research with regard to ELF EMF and health. This report provides an overview of the cumulative body of research published since the WHO review (January 1, 2006-October 1, 2010) and provides the reader with perspective on if, and how, recent research changes the WHO's conclusions.

A summary of the methods scientists use to conduct studies and make decisions about health risks is included in Section 1 as a framework for understanding later discussions. In Section 2, the discussion of new research is broadly grouped by health outcome—cancer, reproductive effects, developmental effects, and neurodegenerative diseases. This discussion summarizes two types of research—epidemiology studies and experimental studies in animals (*in vivo*)—within each health outcome category. Experimental studies in cells and tissues (*in vitro*) of carcinogenesis are discussed briefly in Section 2. Other areas of research not reviewed by WHO are discussed in Section 3, including the possible effects of ELF EMF on the functioning of pacemakers, on flora and fauna, and on marine life. Finally, guidelines for ELF EMF exposure developed by scientific organizations to prevent against established health effects are summarized in Section 4.

1 Scientific Methods

Weight-of-evidence review

Most of what we encounter in our every day environment has no effect on our health. Other exposures, however, may affect our health in either a beneficial or a harmful way, including such ubiquitous interactions with our environment as the air we breathe, the water we drink, and our exposure to sunlight. Much time and money is spent by scientists around the world designing, conducting, and publishing research to determine what factors may affect our health, including environmental exposures (like ELF EMF), infectious agents, and our genetics. The process for arriving at a conclusion about whether there is a health risk associated with any of these factors often is not straightforward or definitive. Rather, it is a long process that requires repeated hypothesis generation and testing.

The process begins when a scientist forms a hypothesis and conducts a study to test that hypothesis. Studies are conducted by scientists at academic universities and scientific institutions around the world. Once a study is complete, the authors submit it to a scientific journal for publication, where it undergoes peer review prior to publication. The evidence to evaluate any health risk includes all of the relevant studies published in the peer-reviewed literature.

These individual research studies can be thought of as puzzle pieces. When all of the research is placed together, we have some understanding of possible health effects; no conclusions can be reached, however, by looking at only one study, just as no picture can be formed with just one puzzle piece. Each study provides a different piece of information to the puzzle because of its unique strengths and weaknesses—if the study used valid methods and had no obvious sources of bias, it may provide a wealth of information or, if the study was not well conducted, it may add little or no information to our understanding.

This process of evaluating all of the research together to determine whether something poses either a health benefit or health risk is referred to as a weight-of-evidence review. There are

three types of research that are considered in a weight-of-evidence review: epidemiology studies of people, experimental studies in animals (*in vivo* research), and experimental studies in cells and tissues (*in vitro* research). It is important to consider all three types of research together because they provide complementary information:

- Epidemiology studies collect observational data about human populations in their every day environments to determine whether there are patterns between exposures and diseases. These studies measure statistical associations to evaluate whether a disease and exposure occur together more often than expected. An important limitation of these studies is that, if an association is measured, they do not tell scientists how the exposure is truly related to the disease. That conclusion can only be reached by considering the entire body of research. Most of the studies evaluating ELF EMF examine whether people with a particular disease have had higher estimates of ELF EMF exposure in the past compared to people without that disease.

- Experimental studies in which scientists expose animals (*in vivo*) to varying levels of electric or magnetic fields (some as high as 50,000 mG) are an important source of information. These studies compare the amount of disease they observe in exposed animals to the amount of disease they observe in animals that have not been exposed. The strength of animal studies is that scientists are able to control all aspects of the animals' lives to minimize the potential confounding effects of factors other than the exposure of interest. The most valuable experimental studies for understanding disease are those in which the animals receive life-long exposures.

- Experimental studies *in vitro* involve the exposure of isolated cells and tissues to the agent of interest, in this case ELF EMF, and compare the characteristics of exposed and unexposed samples to look for differences that are indicative of a disease process. These studies are limited because what occurs to exposed cells or tissues outside of a human body may not be the same as what occurs to cells and tissues inside a body.

The weight-of-evidence approach is the standard process used worldwide by scientists, scientific organizations, and regulatory agencies to assess the possible health benefits and risks associated with exposures. A weight-of-evidence review begins with a systematic review of published, peer-reviewed epidemiology, *in vivo*, and *in vitro* research. The weight that individual studies provide to the overall conclusions is not equal—studies vary widely in terms of the sophistication and validity of their methods. Therefore, each study from each discipline must be evaluated critically and assigned a weight. A final conclusion is then reached by considering the cumulative body of research, giving more weight to studies of higher quality (Figure 1).

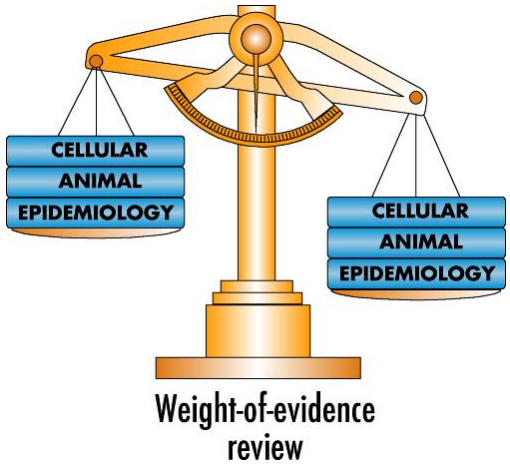


Figure 1. Weight-of-evidence reviews consider three types of research

Continuing with the puzzle example from above, the picture that is formed when the individual studies are assembled can take on many different shapes. In some cases (e.g., smoking and lung cancer), a clear picture of an adverse health effect was presented by the research within a relatively short time. In most cases, however, the picture is unclear and more questions are raised than answered. It is impossible to prove the negative in science—i.e., to say that any exposure is completely safe—therefore, research studies can only reduce the uncertainty that there is a health effect through continued research. The only way to reduce this uncertainty is to conduct high quality studies with meaningful results that are replicated across study populations (in the case of epidemiology studies) and by different laboratories (in the case of *in vivo* and *in vitro* research). Thus, in most areas of research, unless the data clearly indicate an increased

risk at defined exposure levels, scientific panels will conclude that the research is inadequate or limited and requires further study until the uncertainty has been reduced below an acceptable level. While the public may interpret this conclusion as indicating concern, it is natural for scientists to recommend future research to reduce uncertainty around a largely negative body of research or to replicate findings that appear positive.

Scientific and health organizations put together panels of scientists to conduct weight-of-evidence reviews. These panels consist of experts from around the world in the areas of interest (e.g., epidemiology, neurophysiology, toxicology, etc.) and they follow standard scientific methods for arriving at conclusions about possible health risks. The conclusions of these reviews are looked to for the current scientific consensus on a particular topic and form the basis of recommendations made by organizations and governments on exposure standards and precautionary measures.

Scientific reviews on ELF EMF

Numerous national and international organizations responsible for public health have convened multidisciplinary panels of scientists to conduct weight-of-evidence reviews and arrive at conclusions about the possible risks associated with ELF EMF. These organizations include the following (in ascending, chronological order of their most recent publication):

- The **National Institute for Environmental Health Sciences** (**NIEHS**) in the United States assembled a 30-person Working Group to review the cumulative body of epidemiologic and experimental data on ELF EMF and provide conclusions and recommendations to the government (NIEHS, 1998, 1999).

- The **International Agency for Research on Cancer** (**IARC**) completed a full carcinogenic evaluation of ELF EMF in 2002 (IARC, 2002).

- The **World Health Organization (WHO)** released a review in June 2007 as part of its International EMF Program to assess the scientific evidence related to ELF EMF in the frequency range from 0 to 300 GHz (WHO, 2007a). Appendix 1 summarizes the conclusions of this review.

- The **Swedish Radiation Protection Authority (SSI),**[4] using other major scientific reviews as a starting point, evaluated new studies in consecutive annual reports (SSI, 2007; SSI, 2008).

- The **Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR)** issued a report in March 2007 and March 2009 (SCENIHR, 2007; SCENIHR, 2009) updating previous conclusions (SSC, 1998; CSTEE, 2001) to the Health Directorate of the European Commission.

- The **National Radiological Protection Board** (**NRPB**)[5] of the United Kingdom issued full evaluations of the research in 1992, 2001, and 2004, with supplemental updates (NRPB, 1993; NRPB, 1994a) and topic-specific reports (NRPB, 1994b; NRPB, 2001b; HPA, 2006) published in the interim. In a letter addressing a related topic, the Director of the Health Protection Agency of Great Britain (HPA) reiterated their position on ELF EMF and appropriate precautionary measures (HMG, 2009).

- The **International Commission on Non-Ionizing Radiation Protection** (**ICNIRP**), the formally recognized organization for providing guidance on standards for non-ionizing radiation exposure for the WHO**,** published a review of the cumulative body of epidemiologic and experimental data on ELF EMF in 2003. The ICNIRP released draft exposure guidelines for ELF EMF in July 2009 (ICNIRP, 2009). While the ICNIRP panel stated that they relied heavily on previous reviews of the literature related to long-term ELF EMF exposures, they provided relevant conclusions as part of the drafting of these guidelines.

Dissenting opinion on ELF EMF

In August 2007, an *ad hoc* group of 14 scientists and public health and policy consultants published an on-line report titled "*The BioInitiative Report: A Rationale for a Biologically-*

[4] The Swedish Radiation Safety Authority (Sträl säkerhets myndigheten [SSM]) has superseded the SSI, which ceased to exist on 30 June 2008. The SSM is a managing authority of Sweden's Ministry of the Environment and has "national collective responsibility within the areas of radiation protection and nuclear safety," which includes EMF research (http://www.stralsakerhetsmyndigheten.se).

[5] The NRPB merged with the Health Protection Agency in April 2005 to form its new Radiation Protection Division.

based Public Exposure Standard for Electromagnetic Fields (ELF and RF)." The group's objective was to "assess scientific evidence on health impacts from electromagnetic radiation below current public exposure limits and evaluate what changes in these limits are warranted now to reduce possible public health risks in the future" (p. 4). The report was followed by several publications related to ELF EMF that summarized some of the online report's conclusions (Hardell and Sage, 2008; Davanipour and Sobel, 2009; Johansson 2009). The individuals who comprised this group did not represent any well-established regulatory agency nor were they convened by a recognized scientific authority. The report has been criticized by scientific agencies because it did not follow the methods of a standard weight-of-evidence review and, for this reason, its conclusions and recommendations are not considered further in this report (Danish National Board of Health, 2007; ACRBR, 2008; HCN, 2008).[6] Appendix 3 provides a full criticism of the report.

Epidemiology basics

This section briefly describes the main types of epidemiology studies and the major issues that are relevant to evaluating their results. The two, main types of epidemiology studies are cohort studies and case-control studies (Figure 2).

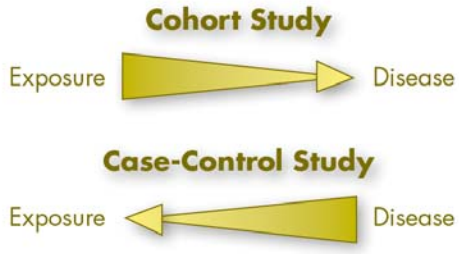


Figure 2. Basic design of cohort and case-control studies

A case-control study compares the characteristics of people that have been diagnosed with a disease (i.e., cases) to a similar group of people who do not have the disease (i.e., controls). The prevalence and extent of past exposure to a particular agent is estimated in both groups and

[6] http://www.gezondheidsraad.nl/en/publications/bioinitiative-report-0

compared to assess whether the cases have a higher exposure level than the controls, or vice versa.

In a case-control study, this comparison (or statistical association) is estimated quantitatively with an odds ratio (OR). An OR is the ratio of the odds of exposure among persons with a disease to the odds of exposure among persons without a disease. The general interpretation of an OR equal to 1.0 is that the odds of exposure are the same in the case and control groups (i.e., there is no statistical association between the exposure and disease). If the OR is greater than 1.0, the inference is that the odds of exposure are greater in the case group or, in other words, the exposure may increase the risk of the disease (Figure 3).

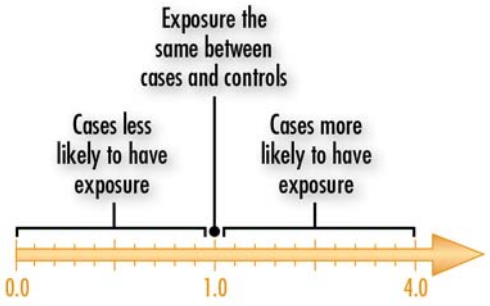


Figure 3. Interpretation of an odds ratio in a case-control study

Each OR is reported with a confidence interval (CI), which is a range of OR values that have a specified probability of occurring if the study is assumed to be repeated a large number of times. A 95% CI, for example, provides the range of values that are likely to occur in 95% of repeated experiments. In short, a CI indicates how certain (or confident) the researcher is about the OR calculated from his or her data; if the CI includes 1.0, the researcher cannot statistically exclude the possibility that the OR is 1.0, meaning the odds of exposure are the same in the case and control groups.

A cohort study is conducted in the reverse manner—in the most traditional sense, researchers study a population *without disease* and follow them over time to see if persons with a certain

exposure develop disease at a higher rate than unexposed persons. The comparisons conducted in cohort studies are similar to the comparisons conducted in case-control studies, although the risk estimate is referred to as a relative risk (RR) rather than an OR. The RR is equal to rate of disease in the exposed group divided by the rate of disease in the unexposed group, with values greater than 1.0 suggesting that the exposed group has a higher rate of disease.

The resulting RR or OR is simply a comparative measure of how often a disease and exposure occur together in exposed and unexposed study populations—it does not mean that there is a known or causal relationship. Before any conclusions can be drawn, all studies considering a particular exposure and disease must be identified, and each study must be evaluated to determine the possible role that factors such as chance, bias, and confounding may have played in the study's results.

- *Chance* refers to a random event, i.e., a coincidence. An association can be observed between an exposure and disease that simply is the result of a chance occurrence. Statistics, such as the CI, are calculated to determine whether chance is a likely explanation for the findings.
- *Bias* refers to any error in the design, conduct, or analysis of a study that would cause a distorted estimate of an exposure's effect on the risk of disease. There are many different types of bias; for example, selection bias may occur if the characteristics of persons that participate in a study differ in a meaningful way from the characteristics of those subjects that do not participate (e.g., cases living near power lines might be more likely to participate than controls because the cases are concerned about this possible exposure).
- *Confounding* is a situation in which an association is distorted because the exposure being studied is associated with other risk factors for the disease. For example, a link between coffee drinking in mothers and low birth weight babies may be observed in a study, but some women who drink coffee also smoke cigarettes. When the smoking habits of mothers are taken into account, coffee drinking may not be associated with low birth weight babies because the confounding effect of smoking has been removed.

As part of the weight-of-evidence review process, each study's design and methods are evaluated critically to determine if and how chance, bias, and confounding may have affected the results and, subsequently, the weight that should be placed on the study's findings.

IARC classifications

This section briefly describes the method that the IARC uses following a weight-of-evidence review to classify exposures based on the evidence in support of carcinogenicity. The WHO adopted this method in their 2007 review on ELF EMF, and other scientific agencies refer to this classification system, as well.

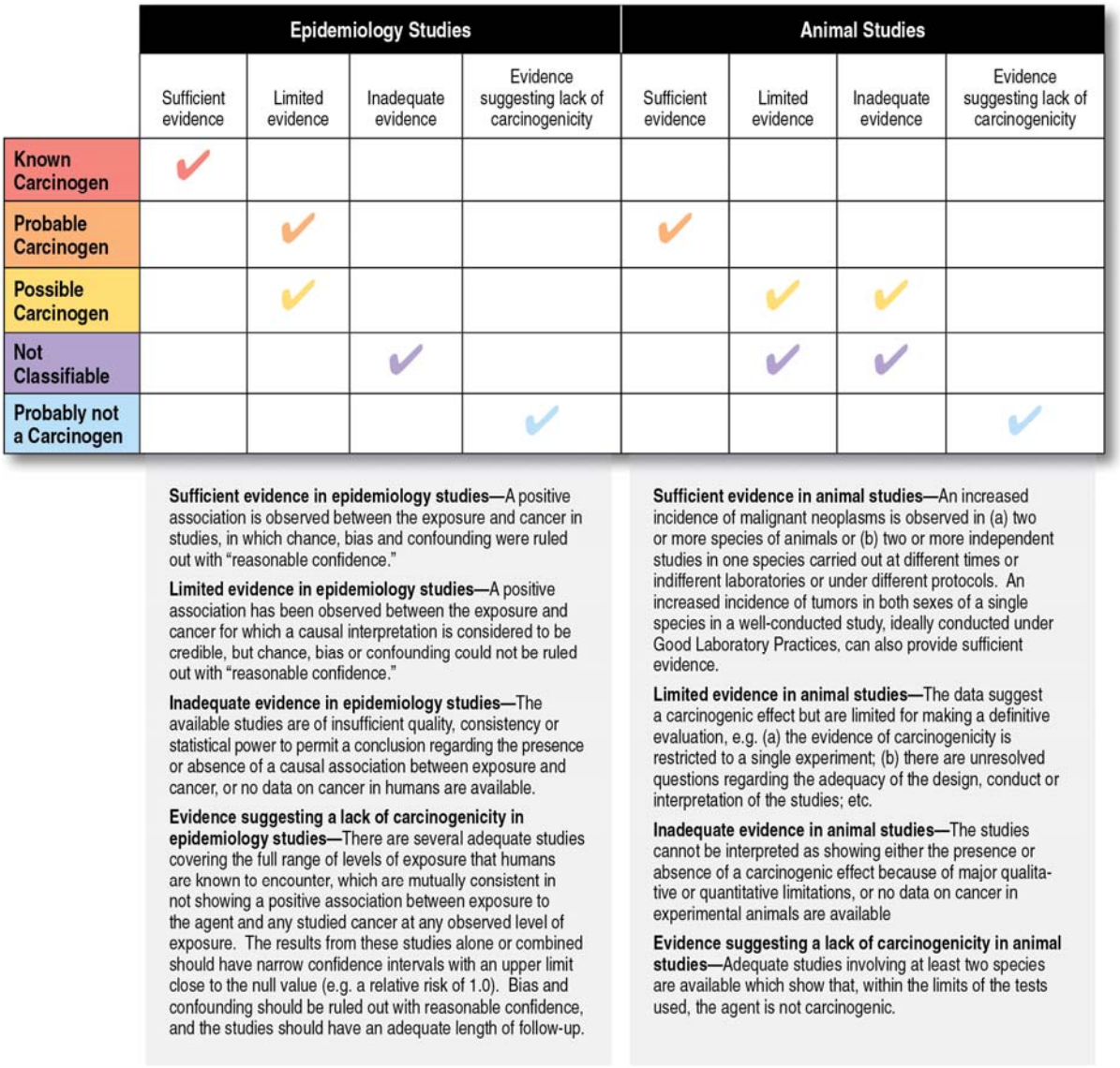
First, each research type (epidemiology, *in vivo*, and *in vitro*) is evaluated to determine the strength of evidence in support of carcinogenicity (as defined in Figure 4). Epidemiology studies are characterized as having *sufficient evidence* for carcinogenicity if an association is found and chance, bias, and confounding can be ruled out with "reasonable confidence." *Limited evidence* is used to describe a body of research where the findings are inconsistent or where an association is observed but there are outstanding questions about study design or other methodological issues that preclude making strong conclusions. *Inadequate evidence* describes a body of research where it is unclear whether the data is supportive or unsupportive of causation because there is a lack of data or there are major quantitative or qualitative issues. The same overall categories apply for *in vivo* research. *In vitro* research is not described in Figure 4 because it provides ancillary information and, therefore, is used to a lesser degree in evaluating carcinogenicity and is classified simply as strong, moderate, or weak.

Agents are then classified into five overall categories using the combined categories from epidemiology, *in vivo*, and *in vitro* research (listed from highest to lowest risk): (1) known carcinogen, (2) probable carcinogen, (3) possible carcinogen, (4) non-classifiable, and (5) probably not a carcinogen.

As summarized in Figure 4, the category possible carcinogen typically denotes exposures for which there is limited evidence of carcinogenicity in epidemiology studies, and *in vivo* studies provide limited or inadequate evidence of carcinogenicity.

The IARC has reviewed over 900 substances and exposure circumstances to evaluate their potential carcinogenicity. Figure 5 provides examples of some of the more common exposures that have been classified in each category. As Figure 5 shows, over 80% of exposures fall in the categories possible carcinogen (27%) or non-classifiable (55%). This occurs because, as described above, it is nearly impossible to prove that something is completely safe and few exposures show a clear-cut or probable risk, so most agents will end up in either of these two categories. Throughout the history of the IARC, only one agent has been classified as probably not a carcinogen, which illustrates the conservatism of the evaluations and the difficulty in proving the absence of an effect beyond all doubt.

Over half of the agents are non-classifiable in terms of carcinogenicity, i.e., it is unclear whether they can cause cancer—hair coloring products, jet fuel, and tea are included in this category. Possible carcinogens include occupation as a firefighter, coffee, and pickled vegetables, in addition to magnetic fields. Exposures identified as probable carcinogens include high temperature frying and occupation as a hairdresser. Finally, known carcinogens include benzene, asbestos, solar radiation, use of tanning beds, and tobacco smoking. As Figure 5 shows, there is much uncertainty about whether certain agents will lead to cancer, and possible and probable carcinogens include substances to which we are commonly exposed or are common exposure circumstances.



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

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

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

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

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

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

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

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

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

Figure 4. Basic IARC method for classifying exposures based on potential carcinogenicity

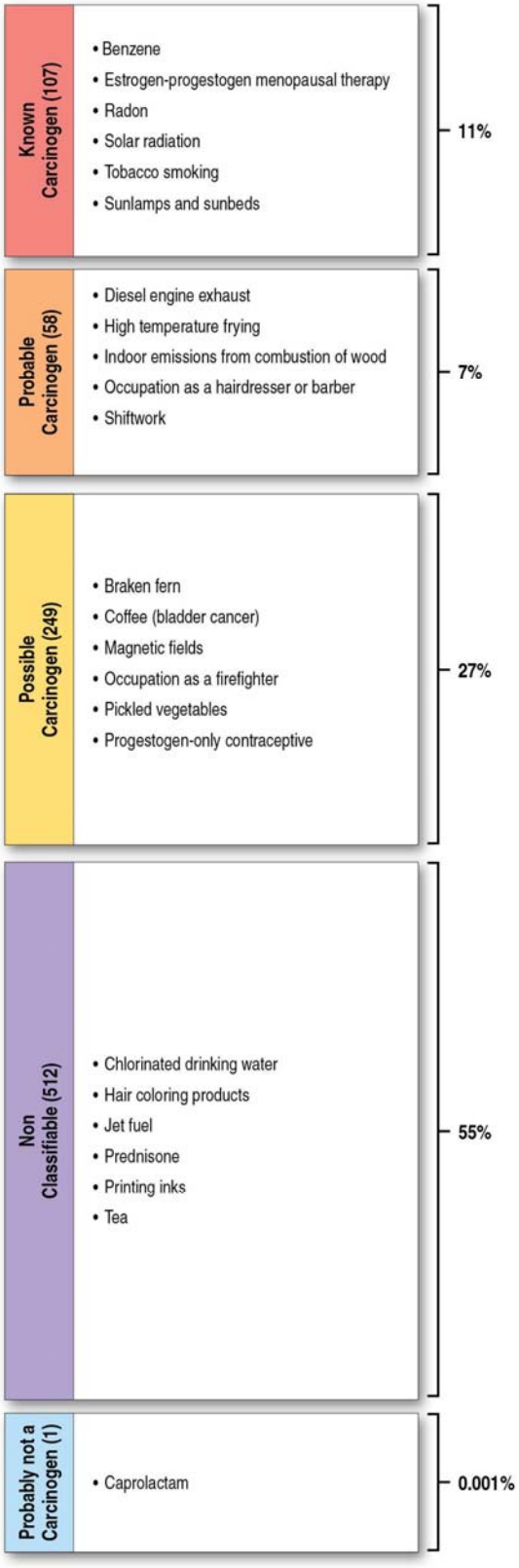


Figure 5. Percentage of substances classified in each IARC category with examples

2 Human Health Research

The following sections provide an overview of peer-reviewed research published between January 1, 2006 and October 1, 2010. A literature review was conducted to identify new epidemiologic, *in vivo,* and *in vitro* research published on 50 or 60-Hz ELF EMF. A large number of search strings referencing the exposure and diseases of interest, as well as authors who regularly publish in this area, were included as search terms in the PubMed database, a service of the U.S. National Library of Medicine that includes over 17 million citations from MEDLINE and other life science journals for biomedical articles dating to the 1950s.[7] A scientist with experience in this area reviewed the search results to identify relevant studies.

This report focuses on the diseases that have received the most attention—cancer, reproductive effects, developmental effects, and neurodegenerative diseases. Other health effects have been studied (i.e., rare cancer types, suicide, depression, electrical hypersensitivity, and cardiovascular effects), but for brevity and because research on these topics evolves slowly, these topics are not summarized here. The WHO review provides a good resource for the status of research on these additional health effects.

This update focuses on identifying and summarizing new epidemiologic and major *in vivo* research, since these study types are the most informative for risk assessment in this field; for the status of *in vitro* research, we include our discussion from the July 2007 report.

Cancer

Childhood leukemia

What was previously known about childhood leukemia and what did the WHO review conclude?

Scientific panels have concluded consistently that magnetic fields are a possible carcinogen largely because of findings from studies of childhood leukemia. Since 1979, approximately 35

[7] PubMed includes links to full text articles and other related resources (http://www.ncbi.nlm.nih.gov/PubMed/).

studies conducted in the United States, Canada, Europe, New Zealand, and Asia have evaluated the relationship between childhood leukemia and magnetic fields using various methods to estimate exposure. These methods have included long-term (48-hour) personal monitoring; spot or long-term (24- or 48-hour) measurements in structures and outdoors; calculations using loading, line configuration, and distance of nearby power installations to estimate historical, residential exposure; and wire code categories.[8] As a group of independent studies, they did not show a clear or consistent association between magnetic fields and childhood leukemia. The largest and most methodologically sound case-control studies to estimate personal magnetic field exposure directly did not report a consistent relationship (Linet et al., 1997; McBride et al., 1999; UKCCS, 2000). When two independent pooled analyses combined the data from these case-control studies, however, a statistically significant association was observed between rare average magnetic field exposure above 3-4 mG and childhood leukemia (Ahlbom et al., 2000; Greenland et al., 2000). Both pooled analyses indicated that children with leukemia were about two times more likely to have had estimated magnetic field exposures above 3-4 mG. Average exposures at this level are uncommon; according to the WHO, results from several extensive surveys showed that approximately 0.5–7.0% of children had time-averaged exposures in excess of 3 mG and 0.4–3.3% had time-averaged exposures in excess of 4 mG (WHO, 2007a). While these analyses provide a valuable quantitative summary of the data, pooled analyses are limited by the disparate methods used to collect the underlying data. Questions have been raised as to whether the original studies, particularly those that are large and estimated exposure directly, provide a more valid estimate of the association than the pooled analyses (Elwood, 2006).

Despite the association observed in these pooled analyses, health agencies have not concluded that magnetic fields are a known or probable cause of childhood leukemia. The studies are of insufficient strength to rule out with "reasonable confidence" the role that chance, bias, and confounding may have had on the observed statistical association. In other words, researchers do not have enough confidence in the way these studies were conducted to conclude that the measured statistical association represents a true relationship between magnetic fields and childhood leukemia. Furthermore, experimental data do not provide evidence for a risk in the

[8] Wire code categories are categories used to classify the potential magnetic field exposures at residences based on the characteristics of nearby power installations.

more highly-controlled *in vivo* studies, and *in vitro* studies do not provide evidence of a plausible biological mechanism whereby magnetic fields lead to carcinogenesis.

Since chance, bias, and confounding could not be ruled out as an explanation for the association, the IARC concluded in 2002 that the data on childhood leukemia provided limited evidence of carcinogenicity (IARC, 2002). In 2007, the WHO reviewed studies on childhood leukemia and magnetic field exposure published since the 2002 IARC review (WHO, 2007a). They concluded that the new epidemiologic studies were consistent with the classification of limited epidemiologic evidence in support of carcinogenicity and, together with the largely negative *in vivo* and *in vitro* research, consistent with the classification of magnetic fields as a possible carcinogen (Figure 4).[9]

Since it is unclear whether the association is real, the WHO review evaluated other factors that might be partially, or fully, responsible for the association, including chance, control selection bias, confounding from hypothesized or unknown risk factors, and misclassification of magnetic field exposure (Figure 6). The following is a summary of their evaluation:

- ✓ The WHO review concluded that **chance** is an unlikely explanation since the pooled analyses had a large sample size and decreased variability.

- ✓ **Control selection bias** occurs when the controls that decide to participate in the study do not represent the true exposure experience of the non-diseased population. In the case of magnetic fields, the WHO speculates that controls with a higher socioeconomic status (SES) may participate in studies more often than controls with a lower SES. Since persons with a higher SES may have lower magnetic field exposures or tend to live farther from transmission lines, the control group's magnetic field exposure may be artificially low. Thus, when the exposure experience of the control group is compared to the case group, there is a difference between the case and control group that does not exist in the source population. The WHO concluded that **control selection bias** is

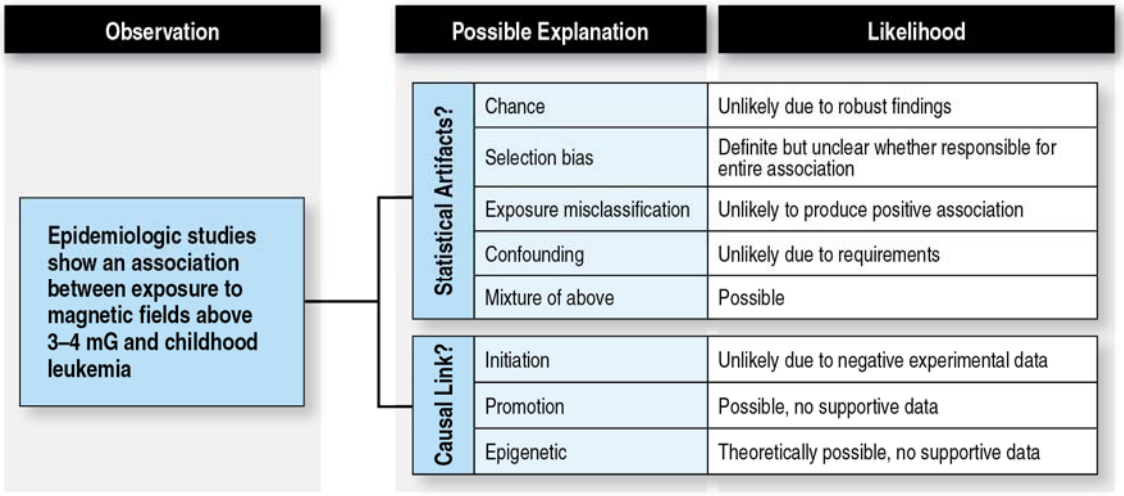
[9] The WHO concluded the following: "Consistent epidemiological evidence suggests that chronic low intensity ELF magnetic field exposure is associated with an increased risk of childhood leukaemia. However, the evidence for a causal relationship is limited, therefore exposure limits based upon epidemiological evidence are not recommended, but some precautionary measures are warranted" (p. 355-6, WHO, 2007a).

probably occurring in these studies and would result in an overestimate of the true association, but would not explain the entire observed statistical association

- ✓ The WHO panel concluded that **confounding** is less likely to be causing the observed association than other factors, although the possibility that some yet-to-be identified confounder is responsible for the association cannot be excluded completely. Suggested risk factors that may be confounding the relationship include SES, residential mobility, contact currents, and traffic density.[10]

- ✓ The WHO stated that the possible effects of **exposure misclassification** are the most difficult to predict. EMF presents unique challenges in exposure assessment because it is ubiquitous, imperceptible, and has many sources (Kheifets and Oksuzyan, 2008). No target exposure or exposure window has been identified, and the numerous methods of estimating exposure likely result in a different degree of error within and between studies. Most reviews have concluded that exposure misclassification would likely result in an underestimate of the true association, meaning the association we observe is lower than the true value; however, the extent to which this might occur varies widely and is difficult to assess (Greenland et al., 2000). The WHO concluded that exposure misclassification likely is present in these studies, but is unlikely to provide an entire explanation for the association.

[10] For example, if dwellings near power lines encounter higher traffic density and pollution from traffic density causes childhood leukemia, traffic density may cause an association between magnetic field exposure and childhood leukemia, where a relationship does not truly exist.



Source: Adapted from Schüz and Ahlbom (2008)

Figure 6. Possible explanations for the observed association between magnetic fields and childhood leukemia

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

What relevant studies have been published since the WHO review?

A number of studies investigating childhood leukemia and magnetic fields have been published since the WHO review (Table 1). Recent studies continue to support a weak association between elevated magnetic field levels and childhood leukemia, but they lack the methodological improvements required to advance this field; the evidence remains limited and the observed statistical association is still unexplained. Some scientists have opined that epidemiology has reached its limits in this area and any future research must demonstrate a significant methodological advancement (e.g., an improved exposure metric or a large sample size in high exposure categories) to be justified (Savitz, 2010; Schmiedel and Blettner, 2010).

Most notably, Kheifets et al. (2010) conducted a pooled analysis of studies published between 2000 and 2010 that was intended to mirror the earlier pooled analyses of studies published between 1974 and 1999 (Ahlbom et al., 2000; Greenland et al., 2000). Kheifets et al. identified six studies for the main analysis that met their inclusion criteria (i.e., population-based studies of childhood leukemia that measured or calculated magnetic fields inside a home); three of the studies in this analysis were considered in the WHO review, while two are described here (Kroll et al., 2010; Malagoli et al., 2010).[11] An additional Brazilian study remains unpublished, but the results were provided via personal communication to Kheifets et al. (Wunsch Filho, personal communication, 2009).[12] A large number of cases were identified by Kheifets et al. (10,865), but a relatively small number of cases (23) were classified in the highest exposure category (>3 mG). A positive association was reported (OR=1.44), but it was weaker than the previous pooled estimates and not statistically significant (95% CI=0.88–2.36); a dose-response relationship was apparent and the association was stronger when the Brazilian study was excluded.

The largest number of cases in Kheifets et al. (2010) was from a large, case-control study conducted in the United Kingdom by Kroll et al. (2010). Kroll et al. expands upon an earlier study (Draper et al., 2005) by replacing residential distance to nearby transmission lines as the exposure metric with calculated magnetic fields from nearby transmission lines; both studies included all children diagnosed with cancer in the United Kingdom from 1962 through 1995. Draper et al. (2005) reported that children with leukemia were more likely to have lived at birth within 600 meters (m) of a high-voltage transmission line, although the authors questioned the significance of this finding since magnetic fields from power lines do not extend to distances of 600 m.[13] Kroll et al. calculated average yearly residential magnetic-field levels for children

[11] A seventh study was included in Kheifets et al. (2010), but only in the pooled analysis of childhood leukemia and residential distance to power lines (Lowenthal et al., 2007). This study is not discussed further in this section because published findings only report on a combined category of lymphoproliferative and myeloproliferative disorders for both adults and children combined.

[12] The study evaluated acute lymphoblastic leukemia among children less than 8 years of age and measured exposure using 24-hour measurements in the children's bedrooms.

[13] The WHO concluded the following with respect to the Draper et al. (2005) findings: "[the] observation of the excess risk so far from the power lines, both noted by the authors and others, is surprising. Furthermore, distance is known to be a very poor predictor of magnetic field exposure, and therefore, results of this material based on calculated magnetic fields, when completed, should be much more informative" (p. 270, WHO 2007a).

living within 400 m of power lines at birth; modeling estimated that magnetic field levels above 1 mG could be predicted reliability only at residences within 400 m of a transmission line. Only 1% of children had a residence at birth within 400 m of a transmission line and only 0.07% had calculated exposures greater than 1 mG. Furthermore, nearly 25% of the residences within 400 m of a transmission line lacked data to calculate residential magnetic-field levels. An OR of 2.0 was calculated for the two cases of childhood leukemia and one control with calculated magnetic fields greater than 4 mG (95% CI=0.18 to 22.04); no dose-response relationship was apparent. As a result of small numbers and incomplete information, no strong conclusions can be drawn from this study. The authors stated that the study "slightly strengthens" the evidence for an association between magnetic fields and childhood leukemia.

Malagoli et al. (2010) was also included in the pooled analysis. This Italian study identified all childhood hematological malignancies diagnosed between 1967 and 2007 in two Italian municipalities (64 cases) and recruited four controls per case matched on sex, age, and municipality of residence.[14] Exposure was defined as having lived for at least 6 months prior to diagnosis at a residence with calculated power-line magnetic field levels above 1 mG or above 4 mG; magnetic-field levels were calculated using 2001 average line loading, rather than loading during the year of birth or diagnosis. Few children lived in a residence with power-line magnetic field levels above 1 mG (2 cases and 5 controls) or 4 mG (1 case and 2 controls); thus, estimated associations were unstable. The RR for leukemia and residence in an area with exposure $\geq$1 mG was 3.2 (6.7 adjusting for SES), but the estimate was statistically unstable (95% CI=0.4-23.4), and there was no indication of a dose-response relationship. Similar to Kroll et al. (2010), this study's strength is the lack of participation required, but it is limited by small numbers, the related imprecision, and the lack of an exposure-response relationship.

Two studies published since the WHO review confirmed an association with residential distance to power lines and childhood leukemia (Feizi and Arabi, 2007 [< 500 m vs. >500 m]; Abdul Rahman et al., 2008 [< 200 m vs. >200 m]). While these two studies were excluded from the pooled analysis because they were hospital-based, Kheifets et al. (2010) pooled data on distance and childhood leukemia from other studies and confirmed an elevated OR at distances less than

[14] Hematological cancers include all types of leukemias, lymphomas, and Hodgkin's disease.

200 m. The association remains unexplained, however, and a recent study confirms that distance is a poor proxy for measurements of residential magnetic fields; Maslanyj et al. (2009) reported that only 13% of homes in a 100 m corridor of 220-440-kV power lines had a measured magnetic field level above 2 mG.

Other recent studies were not included in the pooled analysis because they reported on leukemia subgroups and magnetic fields. These studies reported that children with leukemia and estimates of average magnetic-field exposures greater than 3-4 mG had poorer survival (Foliart et al., 2006, 2007; Svendsen et al., 2007); children with Down syndrome and childhood leukemia were more likely to have spot measurements at the door of their home greater than 6 mG compared to children with Down syndrome only (Mejia-Arangure et al., 2007); and one genetic polymorphism related to DNA repair (but with no known relationship to leukemia) was reported to be more common among children with leukemia living close to an electrical installation compared to children with leukemia living at a distance (Yang et al., 2008). The results of these recent studies were limited by small numbers, incomplete adjustment for potential risk factors, and the lack of a biological explanation to explain the observed associations, among other methodological issues. Additional epidemiologic and biological research is required in these new fields of inquiry.

Another new field of inquiry is the relevance of pre- or post-conception EMF exposure of a parent to cancer in their offspring. Hug et al (2010) studied the pre-conception occupational exposures of parents of children with leukemia and compared them to the exposures of parents of healthy children. No association was found between childhood leukemia and magnetic-field exposure pre-conception in either parent. Another recent study reported an association between childhood leukemia and a paternal history of electrical work, but is limited because exposure is based solely on occupational title (Pearce et al., 2007).

Scientists have also pursued the influence of bias and confounding in recent years. Recent studies confirmed that control selection bias appears to be operating in case-control studies of childhood leukemia and magnetic fields, although the exact degree of its influence is still unknown (Mezei and Kheifets, 2006; Mezei et al., 2008a, 2008b). A study has also found that contact currents from residential grounding systems show characteristics of a confounding

variable (Kavet and Hooper, 2009). Finally, a recent study confirmed that the time of day when magnetic-field measurement are made is not contributing to exposure misclassification; no difference in the magnitude or pattern of results was found for nighttime vs. 24-hour or 48-hour measurements, refuting the hypothesis that nighttime exposures are more strongly associated with childhood leukemia because magnetic fields might affect carcinogenesis through a melatonin-driven pathway (Schüz et al., 2007).

In summary, the studies conducted since the WHO review support an association with magnetic fields and childhood leukemia. In particular, scientific data published since the WHO review:

- confirms the rarity of living in close proximity to a power line or having estimated or measured exposures greater than 1 mG;
- confirms a positive association between average magnetic field levels greater than 3 mG and childhood leukemia, but the association cannot be distinguished from chance due to small numbers;
- confirms an association with residential proximity to power lines and childhood leukemia, but reports that distance is not a reliable predictor of in-home magnetic field levels; and,
- suggests that control selection bias may play some role in the observed association.

These findings do not alter previous conclusions that the epidemiologic evidence on magnetic fields and childhood leukemia is limited. Chance, confounding, and several sources of bias cannot be ruled out. Conclusions from reviews (Kheifets and Oksuzyan, 2008; Schüz and Ahlbom, 2008) and scientific organizations (SSI, 2007; SSI, 2008; HCN, 2009; SCENIHR, 2009) published since the WHO review support this conclusion.

Table 1. Relevant studies of childhood leukemia published after the WHO review

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.
Fezei 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.	2006	Magnetic field exposure and long-term survival among children with leukaemia
Foliart et al.	2007	Magnetic field exposure and prognostic factors in childhood leukemia
Hug et al.	2010	Parental occupational exposure to extremely low frequency magnetic fields and childhood cancer: a German case-control study
Kavet and Hooper	2009	Residential magnetic fields and measures of neutral-to-earth voltage: variability within and between residences
Kheifets et al.	2010	Pooled analysis of recent studies on magnetic fields and childhood leukaemia
Kroll et al.	2010	Childhood cancer and magnetic fields from high-voltage power lines in England and Wales: a case-control study
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
Mejia-Arangure et al.	2007	Magnetic fields and acute leukemia in children with Down syndrome
Mezei and Kheifets	2006	Selection bias and its implications for case-control studies: A case study of magnetic field exposure and childhood leukaemia
Mezei et al.	2008a	Assessment of selection bias in the Canadian case-control study of residential magnetic field exposure and childhood leukemia
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
Schüz et al.	2007	Nighttime exposure to electromagnetic fields and childhood leukemia: An extended pooled analysis
Svendson et al.	2007	Exposure to magnetic fields and survival after diagnosis of childhood leukemia: An extended pooled analysis
Yang et al.	2008	Case-only of interactions between DNA repair genes (hMLH1, APEX1, MGMT, XRCC1, and XPD) and low frequency electromagnetic fields in childhood acute leukemia

Childhood brain cancer

What was previously known about childhood brain cancer and what did the WHO review conclude?

The research related to magnetic fields and childhood brain cancer has been less consistent than that observed for childhood leukemia. The WHO review recommended the following:

> *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, WHO 2007a).*

What relevant studies have been published since the WHO review?

The relevant studies of childhood brain cancer and magnetic field exposure are listed in Table 2 below. In response to the WHO recommendation above, Mezei et al. (2008b) conducted a meta-analysis of studies on childhood brain tumors and residential magnetic field exposure. Thirteen epidemiologic studies were identified that used various proxies of magnetic field exposure (distance, wire codes, calculated magnetic fields, and measured magnetic fields). The combined effect estimate was close to 1.0 and not statistically significant, indicating no association between magnetic field exposure and childhood brain tumors. A sub-group of five studies, however, with information on childhood brain tumors and calculated or measured magnetic fields greater than 3-4 mG reported a combined OR that was elevated but not statistically significant (OR=1.68, 95% CI=0.83-3.43). The authors suggested two explanations for this elevated OR. First, they suggested that an increased risk of childhood brain tumors could not be excluded at high exposure levels (i.e., >3-4 mG). Second, they stated that the similarity of this result to the findings of the pooled analyses of childhood leukemia suggests that control selection bias is operating in both analyses. Overall, the authors concluded that the analysis did not find a significant increase in childhood brain cancer risk using various proxies of residential exposure to magnetic fields.

Two case-control studies were completed after this pooled analysis (Kroll et al., 2010; Saito et al., 2010). In their study of 55 cases of childhood brain cancer, Saito et al. (2010) reported that children with brain cancer were more likely to have average magnetic-field exposure levels

greater than 4 mG, compared to children without brain cancer.[15] The association was based on three cases and one control; interpretations of the data were, therefore, limited by small numbers in the upper exposure category. The strength of this study is the exposure assessment; measurements were taken continuously over a weeklong period in the child's bedroom approximately 1 year after diagnosis. An important limitation, however, is the very poor participation rates among study subjects; poor participation rates introduce the possibility of selection bias, among other biases. As described above, Kroll et al. (2010) included 6,584 cases of brain cancer diagnosed over a 33-year period in the United Kingdom. No associations were reported in any analysis of brain cancer, including calculated magnetic fields ≥1-2 mG, 2-4 mG, and 4mG.

Studies of parental occupational magnetic field exposure and childhood brain tumors have produced inconsistent results. In a recent pooled analysis of two Canadian case-control studies, Li et al. (2009) calculated individual maternal occupational magnetic field exposure pre- and post-conception and analyzed these estimates in relation to brain cancer in offspring. Associations were reported between childhood brain cancer and average magnetic-field exposures greater than approximately 3 mG for exposure in the 2 years prior to conception and during conception; no associations were found using the cumulative and peak exposure metrics. More research is required in this area.

Recent studies provide some suggestion of an association between magnetic field exposures prior to diagnosis or *in utero* and the development of childhood brain cancer. The data receive little weight in an overall assessment, however, due to methodological shortcomings. The recent data do not alter the classification of the epidemiologic data in this field as inadequate.

[15] The unpublished results of this study were included in Mezei et al. (2008b).

Table 2. Relevant studies of childhood brain cancer published after the WHO review

Authors	Year	Study
Kroll et al.	2010	Pooled analysis of recent studies on magnetic fields and childhood leukaemia
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

Breast cancer

What was previously known about breast cancer and what did the WHO review conclude?

The WHO reviewed studies of breast cancer and residential magnetic field exposure, electric blanket usage, and occupational magnetic field exposure. These studies did not report consistent associations between magnetic field exposure and breast cancer, and the WHO concluded that, since the recent body of research was higher in quality compared with previous studies, it provided strong support to previous consensus statements that magnetic field exposure does not influence the risk of breast cancer.[16] The WHO recommended no further research with respect to breast cancer and magnetic field exposure.

What relevant studies have been published since the WHO review?

Two case-control studies (McElroy et al., 2007; Ray et al., 2007) and one cohort study (Johansen et al., 2007) have been published, all of which evaluated occupational magnetic field exposure.[17] In addition, a meta-analysis of 15 studies of breast cancer and occupational magnetic field exposure was published (Chen et al., 2010), which included one of the case-control studies (McElroy et al 2007).

[16] The WHO concluded, "Subsequent to the IARC monograph a number of reports have been published concerning the risk of female breast cancer in adults associated with ELF magnetic field exposure. These studies are larger than the previous ones and less susceptible to bias, and overall are negative. With these studies, the evidence for an association between ELF exposure and the risk of breast cancer is weakened considerably and does not support an association of this kind" (p. 307, WHO 2007a).

[17] In addition to the studies described in the text, another study was identified. Peplonska et al. (2007) is a case-control study of female breast cancer reporting associations for a wide range of occupations and industries. It is not considered in depth in this report because no qualitative or quantitative estimates of magnetic field exposure were made, beyond occupation and industry titles.

Ray et al. (2007) was a nested case-control study in a cohort of approximately 250,000 textile workers in China followed for breast cancer incidence, and McElroy et al. (2007) evaluated occupational exposures to high, low, medium, or background EMF levels in a large number of breast cancer cases and controls. Neither study observed a significant association between breast cancer and higher estimated magnetic field exposure. A large cohort study of utility workers in Denmark also reported that women exposed to higher occupational magnetic field levels did not have higher rates of breast cancer (Johansen et al., 2007).

Chen et al. (2010) published a meta-analysis of all published case-control studies of female breast cancer and magnetic field exposure meeting defined inclusion criteria. Fifteen studies published between 2000 and 2009 were identified examining residential and occupational exposure and electric blanket usage. The authors crudely re-categorized data from the original studies to reflect a common comparison of <2 mG and >2mG and reported an overall OR of 0.988 (95% CI = 0.898–1.088). The advantage of this meta-analysis is its very large size. Its main limitation is that data from a wide range of exposure definitions and cut-points were combined.

These studies, particularly the large cohort of utility workers, add to growing support against a causal role for magnetic fields in breast cancer. This is consistent with the conclusion by the SCENIHR, which stated that an association is "unlikely" (p. 7, SCENIHR 2007).

Table 3. Relevant studies of breast cancer published after the WHO review

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
Johansen et al.	2007	Risk for leukaemia and brain and breast cancer among Danish utility workers: A second follow-up
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
Ray et al.	2007	Occupational exposures and breast cancer among women textile workers in Shanghai

Other adult cancers

What was previously known about other adult cancers and what did the WHO review conclude?

In general, scientific panels have concluded that there is not a strong or consistent relationship between other adult cancers (leukemia, lymphoma, or brain cancers) and exposure to magnetic fields; however, the possibility cannot be entirely ruled out because the findings have been inconsistent (IARC, 2002; WHO, 2007a). Stronger findings have not been observed in studies with better exposure assessment methods, which have led scientific panels to conclude that the evidence for an association is weak. The IARC classified the epidemiologic data with regard to adult leukemia, lymphoma, and brain cancer as "inadequate" in 2002, and the WHO confirmed this classification in 2007, with much of the remaining uncertainty attributed to limitations in exposure assessment methods.

Much of the research on EMF and adult cancers is related to occupational exposures, given the higher range of exposures encountered in the occupational environment. The main limitation of these studies, however, has been the methods used to assess exposure, with early studies relying simply on a person's occupational title (often taken from a death certificate) and later studies linking a person's full or partial occupational history to representative average exposures for each occupation (i.e., a job exposure matrix). The latter method, while advanced, still has some important limitations, as highlighted in a review summarizing an expert panel's findings by Kheifets et al. (2009).[18] While a person's occupation may provide some indication of the overall magnitude of their occupational magnetic field exposure, it does not take into account the possible variation in exposure due to different job tasks within occupational titles, the frequency and intensity of contact to relevant exposure sources, or variation by calendar time. Furthermore, since scientists do not know any mechanism by which magnetic fields could lead to cancer, an appropriate exposure metric is unknown.

In order to reduce the remaining uncertainty about whether there is an association between magnetic fields and these cancers, researchers have recommended (1) meta-analyses to clarify

[18] Kheifets et al. (2009) reports on the conclusions of an independent panel organized by the Energy Networks Association in the United Kingdom in 2006 to review the current status of the science on occupational EMF exposure and identify the highest priority research needs.

inconsistencies and (2) better exposure assessment methods that incorporate a greater level of detail on tasks and exposure characteristics such as spark discharge, contact current, harmonics, etc. (WHO, 2007a; Kheifets et al., 2009).

Adult brain cancer

What was previously known about adult brain cancer and what did the WHO review conclude?

As described above, the WHO classified the epidemiologic data on adult brain cancer as inadequate and recommended (1) updating the existing cohorts of occupationally-exposed individuals in Europe and (2) pooling the epidemiologic data on brain cancer and adult leukemia to confirm the absence of an association. [19]

What relevant studies have been published since the WHO review?

Epidemiologic studies published after 2006 on adult brain cancer and EMF exposure are listed in Table 6 and include two case-control studies, two cohort studies, and a meta-analysis, all of which are related to occupational magnetic field exposure.

In response to the WHO's recommendation, two cohorts of approximately 20,000 occupationally-exposed persons each were updated: a cohort of utility workers in Denmark and a cohort of railway workers in Switzerland (Johansen et al., 2007; Röösli et al, 2007a). In both cohorts, brain cancer rates were similar between jobs with high magnetic field exposure and jobs with lower exposures. A case-control study of gliomas was conducted in Australia and reported no associations with higher estimated magnetic field exposure, using a standard job-exposure matrix (Karipidis et al., 2007a). Forssén et al. (2006) performed a large registry-based case-control study of acoustic neuroma and reported no association between higher occupational magnetic field exposures and this benign and rare brain cancer type. Another large case-control study was recently published of gliomas and meningiomas in the United States (Coble et al., 2009). For the first time, the exposure metric in this study incorporated the frequency of exposure to EMF sources, as well as the distance people worked from these sources, on an

[19] The WHO concluded, "In the case of adult brain cancer and leukaemia, the new studies published after the IARC monograph do not change the conclusion that the overall evidence for an association between ELF [EMF] and the risk of these disease remains inadequate" (p. 307, WHO 2007a).

individual basis. The authors also evaluated exposure metrics in addition to the time-weighted average (TWA) exposure (maximum exposed job, total years of exposure above 1.5 mG, cumulative lifetime exposure, and average lifetime exposure). No association was reported between any of these exposure metrics and brain cancer.

As recommended in the WHO review, a meta-analysis of occupationally-exposed cohorts was performed by Khefeits et al. (2008). All relevant publications of occupational EMF exposure and adult leukemia or brain cancer were collected and summary risk estimates were calculated using various schemes to weight and categorize the study data. The authors reported a small and statistically significant increase of leukemia and brain cancer in relation to the highest estimate of magnetic field exposure in the individual studies. Several findings, however, led the authors to conclude that magnetic field exposure is not responsible for the observed associations, including the lack of a consistent pattern among leukemia subtypes when the past and new meta-analyses were compared. In addition, for brain cancer, the recent meta-analysis reported a weaker association than the previous meta-analysis, whereas a stronger association would be expected since the quality of studies has increased over time. The authors concluded, "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" (p. 677).

Recent studies have reduced possible exposure misclassification by improving exposure assessment methods (i.e., the expanded job-exposure matrix in Coble et al., 2009) and attempted to clarify inconsistencies by updating studies and meta-analyzing data (Johansen et al., 2007; Röösli et al., 2007a; Kheifets et al., 2008); however, despite these advancements, no association has been observed. While an association still cannot be *entirely* ruled out because of the remaining deficiencies in exposure assessment methods, the current database of studies provides weak evidence of an association between magnetic fields and brain cancer.[20] The recent report by the SCENIHR described the data on brain cancers as "uncertain" (p. 43, SCENIHR 2009).

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

Table 4. Relevant studies of adult brain cancer published after WHO review

Authors	Year	Study
Coble et al.	2009	Occupational exposure to magnetic fields and the risk of brain tumors
Forssén et al.	2006	Occupational magnetic field exposure and the risk of acoustic neuroma
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 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
Röösli et al.	2007a	Leukaemia, brain tumours and exposure to extremely low frequency magnetic fields: cohort study of Swiss railway employees

Adult leukemia and lymphoma

What was previously known about adult leukemia/lymphoma and what did the WHO review conclude?

The same issues discussed above with regard to adult brain cancer are relevant to research on adult leukemia and lymphoma. The WHO classified the epidemiologic evidence as "inadequate" and recommended updating the existing occupationally-exposed cohorts in Europe and the meta-analysis on occupational magnetic field exposure (p. 307, WHO 2007a).[21]

What relevant studies have been published since the WHO review?

Two cohorts of occupationally-exposed workers and a meta-analysis of occupational magnetic field exposure (all of which were described above) reported on the possible association of occupational magnetic field exposure and adult leukemia. Also, a case-control study described patterns of estimated residential magnetic field exposure and combined lymphoma and leukemia diagnostic categories (Lowenthal et al., 2007).

In the occupational cohort of Swiss railway workers, the authors noted a stronger association among occupations with higher estimates of magnetic field exposures, but the associations were not statistically significant (Röösli et al, 2007a). In the study of Danish utility workers, no increases in leukemia rates were observed in job titles that involved higher exposures to magnetic fields (Johansen et al., 2007). As described above, the updated meta-analysis by

[21] No specific conclusions were provided by the WHO with regard to lymphoma.

Kheifets et al. (2008) reported a weak association between estimated occupational magnetic field exposure and leukemia, but the authors felt that the data was not indicative of a true association.

Lowenthal et al. (2007) grouped cases in five diagnostic categories as lymphoproliferative disorders (LPD) (including acute lymphoblastic leukemia [ALL]) and cases in three diagnostic categories (including acute myeloid leukemia [AML] and other leukemias) as myeloproliferative disorders (MPD). These groups included both adults and children of all ages. The authors estimated exposure by obtaining a lifetime residential history and assessing distance of residences from 88-kV, 110-kV, and 220-kV power lines. They reported elevated, but not statistically significant, ORs for those who lived within 50 m of any of these power lines, and an indication of decreasing ORs with increasing distance. This study adds very little to the existing database of information on adult leukemia and residential exposure, however, because of fundamental limitations. For example, different cancer types were combined as were different ages of diagnosis. It is well known that cancer etiology varies by cancer type, cancer subtype, and diagnostic age.[22]

Very little is known about the etiology of Non-Hodgkin lymphoma (NHL), and few studies have been conducted in relation to magnetic field exposure. In one of the first studies to estimate cumulative occupational magnetic field exposure among NHL cases, Karipidis et al. (2007b) reported a statistically significant association between NHL and the highest category of exposure (OR=1.59, 95% CI=1.07-2.36). Overall, the study was well conducted, with its most significant limitation being the possibility of uncontrolled confounding. In another case-control study of NHL, Wong et al. (2010) identified 649 cases from a hospital in Shanghai. Among numerous questions in the interview, cases and controls were asked whether they had ever lived within 100 m of a high-voltage power line. Results showed no association (i.e., no differences in residential history between cases and controls), but the strength of the study is limited by the use of distance as a proxy for exposure. Of note, the cohort of railway workers in Switzerland did not report an increase in NHL deaths among the more highly exposed workers (Röösli et al, 2007a). Further research in this area is required.

[22] The recent meta-analysis by Kheifets et al. (2010) implies that data are available from Lowenthal et al. (2007) for childhood leukemia as a separate diagnostic category. This information is not publicly accessible, however.

The recent literature also includes a novel study examining whether there are differences in the activity of the natural killer (NK) cell, a cytotoxic immune cell which attacks tumor cells and cells infected with viruses, among persons occupationally exposed to magnetic fields (Gobba et al., 2008). Higher measured magnetic field levels (i.e., >10 mG) during three complete work shifts were associated with reduced NK activity. Future studies are required to replicate this finding and understand the potential significance of NK activity in cancer.

A number of studies of adult leukemia have attempted to clarify inconsistencies by updating studies and meta-analyzing data (Johansen et al., 2007; Kheifets et al., 2008; Röösli et al, 2007a); however, despite these advancements, no clear or statistically significant association has been observed. While an association still cannot be *entirely* ruled out because of the remaining deficiencies in exposure assessment methods, the current database of studies provides weak evidence of an association between magnetic fields and leukemia. Preliminary results related to NHL have been published and require further investigation.

Table 5. Relevant studies of adult leukemia/lymphoma published after the WHO review

Authors	Year	Study
Gobba et al.	2008	Extremely low frequency-magnetic fields (ELF-EMF) occupational exposure and natural killer activity in peripheral blood lymphocytes
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 power frequency magnetic fields and risk of non-Hodgkin lymphoma
Kheifets et al.	2008	Occupational electromagnetic fields and leukemia and brain cancer: An update to two meta-analyses
Lowenthal et al.	2007	Residential exposure to electric power transmission lines and risk of lymphoproliferative and myeloproliferative disorders: a case-control study
Röösli et al.	2007a	Leukaemia, brain tumours and exposure to extremely low frequency magnetic fields: cohort study of Swiss railway employees
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

In vivo studies of carcinogenesis

What was previously known about *in vivo* studies of carcinogenesis and what did the WHO review conclude?

It is standard procedure to conduct studies on laboratory animals to determine whether exposure to a specific agent leads to the development of cancer (USEPA, 2005). This approach is used

because all known human carcinogens cause cancer in laboratory animals. In the field of ELF EMF research, a number of research laboratories have exposed rodents, including those with a particular genetic susceptibility to cancer, to high levels of magnetic fields over the course of the animals' lifetime and performed tissue evaluations to assess the incidence of cancer in many organs. In these studies, magnetic field exposure has been administered alone (to test for the ability of magnetic fields to act as a complete carcinogen), in combination with a known carcinogen (to test for a promotional or co-carcinogenetic effect), or in combination with a known carcinogen and a known promoter (to test for a co-promotional effect).

The WHO review described four large-scale, long-term studies of rodents exposed to magnetic fields over the course of their lifetime that did not report increases in any type of cancer (Mandeville et al., 1997; Yasui et al., 1997; Boorman et al., 1999a, 1999b; McCormick et al., 1999). No directly relevant animal model for childhood ALL existed at the time of the WHO report. Some animals, however, develop a type of lymphoma similar to childhood ALL and studies exposing predisposed transgenic mice to ELF magnetic fields did not report an increased incidence of lymphoma (Harris et al., 1998; McCormick et al., 1998; Sommer and Lerchel, 2004).

Studies investigating whether exposure to magnetic fields can promote cancer or act as a co-carcinogen used known cancer-causing agents, such as ionizing radiation, ultraviolet radiation, or other chemicals. No effects were observed for studies on chemically-induced preneoplastic liver lesions, leukemia or lymphoma, skin tumors, or brain tumors; however, the incidence of 7,12-dimethylbenz[a]anthracene (DMBA)-induced mammary tumors was increased with magnetic field exposure in a series of experiments in Germany (Löscher et al., 1993, 1994, 1997; Baum et al., 1995; Löscher and Mevissen, 1995; Mevissen et al., 1993a,1993b, 1996a, 1996b, 1998), suggesting that magnetic field exposure increased the proliferation of mammary tumor cells. These results were not replicated in a subsequent series of experiments in a laboratory in the United States (Anderson et al., 1999; Boorman et al.1999a, 1999b), possibly due to differences in experimental protocol and the species strain. In Fedrowitz et al. (2004), exposure enhanced mammary tumor development in one sub-strain (Fischer 344 rats), but not in

another sub-strain that was obtained from the same breeder, which argues against a promotional effect of magnetic fields.[23]

Some studies have reported an increase in genotoxic effects among exposed animals (e.g., DNA strand breaks in the brains of mice [Lai and Singh, 2004]), although the results have not been replicated.

In summary, the WHO concluded the following with respect to *in vivo* 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. 322, WHO 2007a). Recommendations for future research included the development of a rodent model for childhood ALL and the continued investigation of whether magnetic fields can act as a promoter or co-carcinogen.

What relevant studies have been published since the WHO review?

In view of the available evidence that exposure to magnetic fields *alone* does not increase the occurrence of cancer, the literature published following the WHO review includes numerous *in vivo* studies testing different hypotheses of cancer promotion, including effects on brain cancer (Chung et al., 2008), breast cancer (Fedrowitz and Löscher, 2008), and lymphoma or leukemia (Bernard et al., 2008; Negishi et al., 2008), as referenced below. Studies of genotoxicity and oxidative damage *in vivo* have also been published since 2006, but these studies are just conceptually linked to carcinogenicity; this summary focuses on studies of tumor progression since these studies are the most relevant. In each of these studies, the animals were treated first with chemicals known to initiate the cancer process. Initiated animals are more likely to develop cancer, and a subsequent exposure, known as a promoter, is often needed for an initiated cell to reproduce into many cancer cells. Several studies treated the animals with the initiators ethylnitrosourea (ENU) (Chung et al., 2008), n-butylnitrosourea (BNU) (Bernard et al., 2008), and DMBA (Fedrowitz and Löscher, 2008; Negishi et al., 2008). An additional study

[23] The WHO concluded with respect to the German studies of mammary carcinogenesis, "Inconsistent results were obtained that may be due in whole or in part to differences in experimental protocols, such as the use of specific substrains" (p. 321, WHO 2007a).

by Sommer and Lerchel (2006) tested whether magnetic fields alone increased the incidence of lymphoma in mice virally predisposed to lymphoblastic lymphoma.

Chung et al. (2008) examined the possible role of 60-Hz magnetic fields in promoting brain tumors initiated by ENU injections *in utero*; the authors concluded that there was no evidence that exposure to 60-Hz magnetic fields up to 5,000 mG promoted tumor development in this study.

Fedrowitz and Löscher (2008) is the most recent study from the German laboratory that previously reported increases in DMBA-induced mammary tumors with high magnetic field exposure. In this recent study, the researchers exposed DMBA-treated Fischer 344 rats (the strain of inbred rats used in previous experiments) to either high levels of magnetic fields (1,000 mG) or no exposure for 26 weeks and reported that the incidence of mammary tumors was significantly elevated in the group exposed to magnetic fields (Fedrowitz and Löscher, 2008). No independent replication of this experiment has yet occurred and questions still remain about the effect of experimental protocol and species strain.

Sommer and Lerchl (2006) is a follow-up to an earlier study (Sommer and Lerchl, 2004) that reported no increases in lymphoma among predisposed animals chronically exposed to magnetic fields (up to 1,000 mG for 24 hours per day for 32 weeks). Sommer and Lerchl (2006) increased magnetic field exposure to 10,000 mG and exposed some of the animals only during the night to test the hypothesis that nighttime exposure may have a stronger effect than continuous exposure. Magnetic fields did not influence body weight, time to tumor, cancer incidence, or survival time in this study. In another study of lymphatic system cancers, researchers treated newborn mice with DMBA and magnetic fields up to 3,500 mG (Negishi et al., 2008). The authors reported that the percentage of mice with lymphoma or lymphatic leukemia was not higher in magnetic field-exposed groups, compared to the sham-exposed group.

In another study of lymphoid leukemia, Chung et al (2010) evaluated the effect of magnetic fields on AKR mice, which are genetically predisposed to thymic lymphoblastic lymphoma. Exposures ranged from 50-500 mG for 21 hours per day for 40 weeks, and cancer incidence was compared with a sham-exposed control group. Potential confounding variables (such as

temperature, humidity, and magnetic-field variations) were monitored daily. The experiment was performed blind to ensure that biases were not introduced by investigator knowledge of exposure conditions. Magnetic-field exposures were not associated with changes in body weight, survival time, or the incidence of lymphoma compared to sham-treated controls. Exposure also did not affect components of the blood, micronuclei formation, or gene expression in the thymus.

A study by Bernard et al. (2008) provides a significant development, in that it is the first study to use an animal model of ALL, the most common leukemia type in children. All rats were exposed to BNU to initiate the leukemogenic process, and a sub-group of rats was exposed to magnetic fields of 1,000 mG for 18 hours per day for 52 weeks. No difference in leukemia incidence was observed between the BNU-treated group exposed to magnetic fields and the BNU-treated unexposed group. This study supports the hypothesis that magnetic fields do not affect the development of ALL and provides additional support to the conclusion that experimental data is not supportive for a role of magnetic fields in the incidence of childhood leukemia. The researchers followed guidelines for the experimentation and care of laboratory animals and conducted the analyses blind to the treatment group. Experience with this strain of rat is limited, however, so it is unclear whether the results are more or less reliable than other animal models; replication is required.

Thus, aside from the most recent replication of enhanced mammary carcinogenesis in a specific sub-strain of rats in a German laboratory, recent studies provide further evidence against a role for magnetic fields as a co-carcinogen. These studies strengthen the conclusion that there is inadequate evidence of carcinogenicity from *in vivo* research, although independent confirmation of the German results is of high priority.

Table 6. Relevant *in vivo* studies of carcinogenesis published after the WHO review

Authors	Year	Study
Bernard et al.	2008	Assessing the potential Leukemogenic effects of 50 Hz and their harmonics using an animal leukemia model
Chung et al.	2008	Lack of a co-promotion effect of 60 Hz rotating magnetic fields on n-ethyl-n-nitrosourea induced neurogenic tumors in F344 rats
Chung et al.	2010	Lack of a co-promotion effect of 60 Hz rotating magnetic fields on N-ethyl-N-nitrosourea induced neurogenic tumors in F344 rats
Fedrowitz and Löscher	2008	Exposure of Fischer 344 rats to a weak power frequency magnetic field facilitates mammary tumorigenesis in the DMBA model of breast cancer
Negishi et al.	2008	Lack of promotion effects of 50 Hz magnetic fields on 7,12-dimethylbenz(a)anthracene-induced malignant lymphoma/lymphatic leukemia in mice
Sommer and Lerchl	2006	50 Hz magnetic fields of 1 mT do not promote lymphoma development in AKR/J mice

In vitro studies of carcinogenesis

What did the WHO and other scientific panels conclude with respect to *in vitro* studies of carcinogenesis?

In vitro studies are widely used to investigate the mechanisms for effects that are observed in humans and animals. The relative value of *in vitro* tests to human health risk assessment, however, is much less than that of *in vivo* and epidemiology studies. Responses of cells and tissues outside the body may not always reflect the response of those same cells if maintained in a living system, so the relevance of *in vitro* studies cannot be assumed (IARC, 1992).

The IARC and other scientific review panels that systematically evaluated *in vitro* studies concluded that there is no clear evidence indicating how ELF magnetic fields could adversely affect biological processes in cells (IARC, 2002; ICNIRP, 2003; NRPB, 2004). The WHO panel reviewed the *in vitro* research published since the time of these reviews and reached the same conclusion. The WHO noted that previous studies have not indicated a genotoxic effect of ELF magnetic fields on mammalian cells, however a series of experiments reported DNA damage in human fibroblasts exposed intermittently to 50 Hz magnetic fields (Ivancsits et al., 2002a, 2002b; Ivancsits et al., 2003a, 2003b). These findings have not been replicated by other laboratories (Scarfi et al., 2005), and the WHO recommended continued research in this area. Recently, investigators reported that they were unable to confirm any evidence for damage to DNA in cells exposed to magnetic fields over a range of exposures from 50 to 10,000 mG (Burdak-Rothkamm et al., 2009). Research in the field of *in vitro* genotoxicity of magnetic

fields combined with known DNA-damaging agents is also recommended, following suggestive findings from several laboratories. As noted by the SSI, however, the levels at which these effects were observed are much higher than the levels to which we are exposed in our everyday environments and are, therefore, not directly relevant to questions about low-level, chronic exposures (SSI, 2007). *In vitro* studies investigating other possible mechanisms, including gene activation, cell proliferation, apoptosis, calcium signaling, intercellular communication, heat shock protein expression, and malignant transformation have produced "inconsistent and inconclusive" results, according to the WHO (p. 347, WHO, 2007a).

Reproductive and developmental effects

What was previously known about reproductive and developmental effects and what did the WHO review conclude?

Two studies received considerable attention because of a reported association between peak magnetic field exposure greater than approximately 16 mG and miscarriage: a prospective cohort study of women in early pregnancy (Li et al., 2002) and a nested case-control study of women who miscarried compared to their late-pregnancy counterparts (Lee et al., 2002).

These two studies improved on the existing body of literature because average exposure was assessed using 24-hour personal magnetic field measurements (early studies on miscarriage were limited because they used surrogate measures of exposure, including visual display terminal use, electric blanket use, or wire code data). Following the publication of these two studies, however, a hypothesis was put forth that the observed association may be the result of behavioral differences between women with "healthy" pregnancies that went to term (less physically active) and women who miscarried (more physically active) (Savitz, 2002). It was proposed that physical activity is associated with an increased opportunity for peak magnetic field exposures, and the nausea experienced in early, healthy pregnancies and the cumbersomeness of late, healthy pregnancies would reduce physical activity levels, thereby decreasing the opportunity for exposure to peak magnetic fields. Furthermore, nearly half of the miscarriages reported in the cohort by Li et al. had magnetic field measurements taken after miscarriage occurred, when changes in physical activity may have already occurred, and all measurements in Lee et al. occurred post-miscarriage.

The scientific panels that have considered these two studies concluded that the possibility of this bias precludes making any conclusions about the effect of magnetic fields on miscarriage (NRPB, 2004; FPTRPC, 2005; WHO, 2007a). The WHO concluded, "There is some evidence for increased risk of miscarriage associated with measured maternal magnetic field exposure, but this evidence is inadequate" (p. 254, WHO 2007a). The WHO stated that, given the potentially high public health impact of such an association, further epidemiologic research is recommended.

What relevant studies have been published since the WHO review?

No new original studies on magnetic field exposure and miscarriage have been conducted; however, recent methodological studies evaluated the likelihood that the observed association was due to bias. Epidemiologic and *in vivo* studies of ELF EMF and reproductive and developmental effects are summarized in Table 7.

It is not possible to directly "test" for the effects of this bias in the original studies, but two recent analyses examined whether reduced physical activity was associated with a lower probability of encountering peak magnetic fields (Mezei et al., 2006; Savitz et al., 2006). In a 7-day study of personal magnetic field measurements in 100 pregnant women, Savitz et al. (2006) reported that active pregnant women were more likely to encounter peak magnetic fields. In addition, an analysis by Mezei et al. (2006) of pre-existing databases of magnetic field measurements among pregnant and non-pregnant women found that increased activity levels were associated with peak magnetic fields. These findings are broadly supportive of the hypothesis that reduced activity among women in early pregnancies because of nausea and in later pregnancies because of cumbersomeness may explain the observed association between peak magnetic fields and miscarriage. As noted in a recent commentary on this issue, however, the possibility that there is a relationship between peak magnetic field exposure and miscarriage still cannot be excluded and further research that accounts for this possible bias should be conducted (Neutra and Li, 2008; Mezei et al., 2006). There remains no biological basis, however, to indicate that magnetic field exposure increases the risk of miscarriage (WHO, 2007a).

Two additional studies were published related to developmental outcomes and growth. Fadel et al. (2006) conducted a cross-sectional study in Egypt of 390 children 0-12 years of age living in an area within 50 m of an electrical power line and 390 children 0-12 years of age living in a region with no power lines in close proximity. Measurements were taken as proxies of growth retardation, and radiological assessments were performed on carpal bones. The authors reported that children living in the region near power lines had a statistically significant lower weight at birth and a reduced head and chest circumference and height at all ages. The authors concluded that "exposure to low frequency electromagnetic fields emerged [*sic*] from high voltage electric power lines increases the incidence of growth retardation among children" (p. 211). This conclusion, however, fails to adequately take into account the many limitations of their cross-sectional analysis (namely, inadequate control for the possible confounding effects of nutritional and SES status) and the pre-existing body of literature, which does not support such an association (WHO, 2007a). Public health statistics indicate that detrimental birth outcomes, including pre-term birth, low birth weight, or small for gestational age, occur more frequently in populations of lower SES (HHS, 2004); thus, analyses of adverse birth outcomes should be adjusted for these factors.

Auger et al. (2010) studied whether maternal residence near transmission lines was associated with adverse birth outcomes, adjusting for socioeconomic factors, among all live births in Montreal and Canada between 1990 and 2004. Maternal residential distances were measured within 400 m of nearby transmission lines for over 700,000 live births, and the proportion of adverse events was compared between mothers living >400 m and within 400 m, adjusting for mother's age, education, household income, and other potential confounding factors. The analysis found no association with distances in 50 m increments for any of the outcomes: pre-term birth, low birth weight, small for gestational age, or proportion of male births. The use of distance as a surrogate of EMF exposure limits the value of this study.

Among recent *in vivo* reproductive studies of ELF EMF, seven examined effects on the female reproductive system (Aksen et al., 2006; Roushanger and Soleimani Rad, 2007; Al-Akhras et al., 2008; Anselmo et al., 2009; Aydin et al., 2009; De Bruyen and De Jager, 2010; Rajaei et al., 2010). In most of these studies, the researchers did not clarify whether they incorporated blinding to minimize bias and failed to indicate whether they used appropriate statistical

analyses (e.g., use of the litter, rather than the pup, as the unit for analysis since littermates are known to be more similar to each other than offspring derived from separate litters). Other limitations included the use of animals with extremely deficient diets and the use of only one magnetic field level so that dose-response could not be assessed. Although some of the studies reported biological changes, none of the studies reported strong evidence of adverse reproductive outcomes.

Studies of reproductive effects on males were conducted across a broad range of exposures and duration and also suffered from flaws that affect validity; most failed to report methods to ensure blinding, and some used short-term exposures to extremely high fields (Al-Akhras et al., 2006; Mostafa et al., 2006; Farkhad et al., 2007; Khaki et al., 2008; Kim et al., 2009; Bernabo et al., 2010). De Bruyn and de Jager (2010) reported decreases in sperm motility that do not translate to functional decrements in reproductive capacity.

Studies also were conducted of exposure during pregnancy (Anselmo et al., 2006, 2008; Okudan et al., 2006; Yao et al., 2007; Dundar et al., 2009; De Bruyn and De Jager, 2010). The studies entailed high and short-term exposures and had specific and narrows goals, e.g., evaluating changes in the eye or bone. Of note, De Bruyn and De Jager (2010) continuously exposed mice to a randomly varying 50-Hz magnetic field between 5mG and 770 mG from conception through two generations of offspring in a double-blind study. Both the treated and sham-exposed groups consisted of ten pairs of mice in each generation. No effects of exposure were observed on mean gestational and generational days, mean litter size, or total number of stillborn pups. Like the other studies, however, the authors did not indicate whether appropriate statistical methods were used to control for potential litter effects.

Thus, the recent epidemiologic research does not provide sufficient evidence to alter the conclusion that the evidence for reproductive or developmental effects is inadequate. Recent studies of animals *in vivo* also do not provide evidence to change the conclusions expressed by the WHO. Various deficiencies in the methods and reporting of these studies limit their use in health risk assessment.

Table 7. Relevant studies of reproductive and developmental effects published after the WHO review

Authors	Year	Study
Aksen et al.	2006	Effect of 50-Hz 1-mT magnetic field on the uterus and ovaries of rats (electron microscopy evaluation)
Al-Akhras et al.	2006	Influence of 50 Hz magnetic field on sex hormones and other fertility parameters of adult male rats
Al-Akhras et al.	2008	Influence of 50 Hz magnetic field on sex hormones and body, uterine, and ovarian weights of adult female rats
Anselmo et al.	2006	Influence of a 60 Hz, 3 microT, electromagnetic field on the reflex maturation of Wistar rats offspring from mothers fed a regional basic diet during pregnancy
Anselmo et al.	2008	Influence of a 60 Hz, microT, electromagnetic field on the somatic maturation of wistar rat offspring fed a regional basic diet during pregnancy
Anselmo et al.	2009	Effects of the electromagnetic field, 60 Hz, 3 microT, on the hormonal and metabolic regulation of undernourished pregnant rats
Auger et al.	2010	The relationship between residential proximity to extremely low frequency power transmission lines and adverse birth outcomes
Aydin et al.	2009	Evaluation of hormonal change, biochemical parameters, and histopathological status of uterus in rats exposed to 50-Hz electromagnetic field
Bernabó et al.	2010	Extremely low frequency electromagnetic field exposure affects fertilization outcome in swine animal model
De Bruyen and De Jager	2010	Effect of long-term exposure to a randomly varied 50 Hz power frequency magnetic field on the fertility of the mouse
Dundar et al.	2009	The effect of the prenatal and post-natal long-term exposure to 50 Hz electric field on growth, pubertal development and IGF-1 levels in female Wistar rats
Fadel et al.	2006	Growth assessment of children exposed to low frequency electromagnetic fields at the Abu Sultan area in Ismailia (Egypt)
Farkhad et al.	2007	Effects of extremely low frequency electromagnetic field on testes in guinea pig
Khaki et al.	2008	The effects of electromagnetic field on the microstructure of seminal vesicles in rat: a light and transmission electron microscope study
Kim et al.	2009	Effects of 60 Hz 14 μT magnetic field on the apoptosis of testicular germ cell in mice
Mezei et al.	2006	Analyses of magnetic-field peak-exposure summary measures
Mostafa et al	2006	Sex hormone status in male rats after exposure to 50 Hz, mT magnetic field
Neutra and Li	2008	Letter to the Editor – Magnetic fields and miscarriage: A commentary on Mezei et al., JESEE 2006
Okudan et al.	2006	DEXA analysis on the bones of rats exposed in utero and neonatally to static and 50 Hz electric fields
Rajei et al.	2010	Effects of extremely low-frequency electromagnetic field on fertility and heights of epithelial cells in pre-implantation stage, endometrium and fallopian tube in mice
Roushanger and Soleimani Rad	2007	Ultrastructural alterations an occurrence of apoptosis in developing follicles exposed to low frequency electromagnetic field in rat ovary
Savitz et al.	2006	Physical activity and magnetic field exposure in pregnancy
Yao et al.	2007	Absence of effect of power-frequency magnetic fields on exposure on mouse embryonic lens development

Neurodegenerative disease

What was previously known about neurodegenerative disease and what did the WHO review conclude?

Research into the possible effect of magnetic fields on the development of neurodegenerative diseases began in 1995, and the majority of research since then has focused on Alzheimer's disease and a specific type of motor neuron disease called amyotrophic lateral sclerosis (ALS), which is also known as Lou Gehrig's disease. The inconsistency of early Alzheimer's disease studies prompted the NRPB to conclude that there is "only weak evidence to suggest that it [ELF magnetic fields] could cause Alzheimer's disease" (p. 20, NRPB, 2001). Early studies on ALS, which had no obvious biases and were well conducted, reported an association between ALS mortality and estimated occupational magnetic field exposure. The review panels, however, were hesitant to conclude that the associations provided strong support for a causal relationship. Rather, they felt that an alternative explanation (i.e., electric shocks received at work) may be the source of the observed association.

The majority of the more recent studies discussed by the WHO reported statistically significant associations between occupational magnetic field exposure and mortality from Alzheimer's disease and ALS, although the design and methods of these studies were relatively weak (e.g., disease status was based on death certificate data, exposure was based on incomplete occupational information from census data, and there was no control for confounding factors). Furthermore, there was no biological data to support an association between magnetic fields and neurodegenerative diseases. The WHO panel concluded that there is "inadequate" data in support of an association between magnetic fields and Alzheimer's disease or ALS.[24] The panel recommended more research in this area using better methods; in particular, studies that enrolled incident Alzheimer's disease cases (rather than ascertaining cases from death certificates) and studies that estimated electrical shock history in ALS cases were recommended.

[24] After considering the entire body of literature and its limitations, the WHO report concluded, "When evaluated across all the studies, there is only very limited evidence of an association between estimated ELF exposure and [Alzheimer's] disease risk" (p. 194, WHO 2007a).

What relevant studies have been published since the WHO review?

Six studies have been published since the WHO review. Two occupational cohorts were followed for neurodegenerative diseases—approximately 20,000 railroad workers in Switzerland (Röösli et al., 2007b) and over 80,000 electrical and generation workers in the United Kingdom (Sorahan and Kheifets, 2007). Two case-control studies collected incident cases of Alzheimer's disease and estimated occupational magnetic field exposure (Davanipour et al., 2007; Seidler et al., 2007), and a meta-analysis was conducted of occupational magnetic field exposure and Alzheimer's disease studies (García et al., 2008). The first study of non-occupational exposure followed the Swiss population to evaluate associations with residential distance to power lines and death due to neurodegenerative diseases (Huss et al., 2009).

García et al. (2008) identified 14 epidemiologic studies with information on Alzheimer's disease and occupational EMF exposure; the WHO considered the majority of these studies in their 2007 review. A statistically significant association between Alzheimer's disease and occupational EMF exposure was observed for both case-control and cohort studies (OR =2.03, 95% CI=1.38-3.00 and RR =1.62, 95% CI=1.16-2.27, respectively), although the results from the individual studies were so different that the authors cautioned against the validity of these combined results. While some subgroup analyses had statistically significant increased risks and were not significantly heterogeneous between studies, the findings were contradictory between study design types (e.g., elevated pooled risk estimates were reported for *men* in cohort studies and elevated pooled risk estimates were reported for *women* in case-control studies). The authors concluded that their results suggest an association between Alzheimer's disease and occupational magnetic field exposure, but noted the numerous limitations associated with these studies, including the difficulty of assessing EMF exposure during the appropriate time period, case ascertainment issues due to diagnostic difficulties, and differences in control selection. They recommended further research that uses more advanced methods.

An earlier publication by the same group of investigators documented the relatively poor quality of the studies included in the meta-analysis. Santibáñez et al. (2007) evaluated studies related to occupational exposure and Alzheimer's disease, which included seven of the studies in the García et al. meta-analysis. Two epidemiologists blindly evaluated each of these studies using a

questionnaire to assess the possibility of a number of biases, with a score assigned to each study that represented the percentage of possible points that the study obtained (range 0-100%). Only one of the seven studies obtained a score above 50% (a retrospective cohort study by Savitz et al. in 1998), and disease and exposure misclassifications were the most prevalent biases.

Davanipour et al. (2007) extended an earlier hypothesis-generating study by Sobel et al. (1996) by collecting cases from eight California Alzheimer's Disease Diagnostic and Treatment Centers. Self-reported primary occupation was collected from patients with verified diagnoses of Alzheimer's disease and compared to occupational information collected from persons diagnosed with other dementia-related problems at the Centers. The results of this study were consistent with the previous studies by Sobel et al.; cases were approximately twice as likely to be classified as having medium/high magnetic field exposures, compared with controls. The strengths of this study included its large size and self-reported occupational information. The main limitation of this study was that the exposure assessment only considered a person's primary occupation, classified as low, medium, or high magnetic field exposure. The WHO noted limitations of the 1996 publication that are relevant to this publication as well, including the use of controls with dementia (which some studies report have an increased risk of Alzheimer's disease) and the classification of seamstresses, dressmakers, and tailors as "high exposure" occupations, which drives the increase in risk.

Seidler et al. (2007) conducted a similar case-control study in Germany, except cases included all types of dementia (55% of which had Alzheimer's disease). Cumulative magnetic field exposure was estimated from occupational histories taken from proxy respondents, and no difference was reported between cases of dementia or probable Alzheimer's disease and controls, although an association was reported among electrical and electronics workers. The authors reported that exposure misclassification was likely to be a significant problem and concluded that their results indicate a strong effect of low-dose EMF is "rather improbable" (p. 114).

Sorahan and Kheifets (2007) followed a cohort of approximately 84,000 electrical and generation workers in the United Kingdom for deaths attributed to neurodegenerative disease on death certificates. Cumulative magnetic field exposure was calculated for each worker, using

job and facility information. The authors reported that the cohort did not have a significantly greater number of deaths due to Alzheimer's disease or motor neuron disease compared to the general population in the United Kingdom. They also reported that persons with higher estimated magnetic field exposures did not have a consistent excess of death due to Alzheimer's disease or motor neuron disease compared to persons with lower estimated magnetic field exposure. A statistically significant excess of deaths due to Parkinson's disease was observed in the cohort, although there was no association between calculated magnetic field exposure and Parkinson's disease. The authors concluded "our results provide no convincing evidence for an association between occupational exposure to magnetic fields and neurodegenerative disease" (p. 14). This result is consistent with two other Alzheimer's mortality follow-up studies of electric utility workers in the United States (Savitz et al., 1998) and Denmark (Johansen and Olsen, 1998). The findings may be limited by the use of death certificate data, but are strengthened by the detailed exposure assessment.

Death from several neurodegenerative conditions was also evaluated in the cohort of more than 20,000 Swiss railway workers described above (Röösli et al., 2007b). Magnetic field exposure was characterized by specific job titles as recorded in employment records; stationmasters were considered to be in the lowest exposure category and were, therefore, used as the reference group. Train drivers were considered to have the highest exposure, and shunting yard engineers and train attendants were considered to have exposure intermediate to stationmasters and train drivers. Cumulative magnetic field exposure was also estimated for each occupation using on-site measurements and modeling of past exposures. The authors reported an excess of senile dementia disease among train drivers, compared to station masters, however, the difference was not statistically significant. The association was larger when restricted to Alzheimer's disease, but was still not statistically significant (hazard ratio [HR]=3.15, 95% CI=0.90-11.04); an association was observed between cumulative magnetic field exposure and Alzheimer's disease/senile dementia. No elevation in mortality was reported for multiple sclerosis, Parkinson's disease, or ALS among train drivers, shunting yard engineers, or train attendants, compared with stationmasters, nor were more deaths from these causes observed for higher estimated magnetic field exposures. Similar to another recent Swedish study (Feychting et al., 2003), the authors reported that recent exposure was more strongly associated with Alzheimer's disease than past exposure.

There are several strengths of this study relative to the existing body of data. First, there is little turnover among Swiss railway employees, which means that study participants are enrolled in the cohort and possibly exposed for long periods of time. The wide variation in exposure levels between different occupations in the same industry allows for comparison of similar workers with different levels of exposure. Another advantage is that the company kept detailed registers of employees, which means there is less potential for bias in the enumeration of the cohort and reconstruction of exposures. Finally, the authors reported that exposures to chemicals or electric shocks, which often occur in other occupational settings (for example, in electric utility workers or welders), are rare in this occupation.

Another cohort study conducted in Switzerland linked all persons older than 30 years of age at the 2000 census with a national database of death certificates from 2000 through 2005 (Huss et al., 2009). Residential location was also extracted from 1990 and 2000 census data and the closest distance of a person's home in 2000 to nearby 220-380 kV transmission lines was calculated. The authors reported that persons living within 50 m of these high-voltage transmission lines were more likely to have died from Alzheimer's disease, compared to those living farther than 600 m, although chance could not be ruled out as an explanation (HR=1.24, 95% CI=0.80-1.92). The association was stronger for persons that lived at the residence for at least 15 years (HR=2.00, 95% CI=1.21-3.33). Associations of similar magnitude were reported for senile dementia and residence within 50 m of a high-voltage line. No associations were reported beyond 50 m for Alzheimer's disease or senile dementia, and no associations were reported at any distance for Parkinson's disease, ALS, or multiple sclerosis.

The study's main limitation is the use of residential distance from transmission lines as a proxy for magnetic-field exposure (Maslanyj et al., 2009). It is also limited by the use of death certificate data, which are known to under-report Alzheimer's disease, and the lack of a full residential and occupational history. Furthermore, while the underlying cohort was very large, relatively few cases of Alzheimer's disease lived within 50 m of a high-voltage transmission line—20 cases total and 15 cases who lived at the residence for at least 15 years. This means that misclassification of a small number of cases could have a large impact on the risk estimate.

Another recent study used Sweden's large twin registry to assess whether occupational exposure to EMF was associated with dementia or Alzheimer's disease (Andel et al., 2010). Twins over the age of 65 were interviewed by phone to screen for possible dementia, and cases were identified for further evaluation to determine whether they had dementia or Alzheimer's disease (cases); study subjects without either diagnosis were considered the control group. Study subjects or their proxies were asked to identify their major lifetime occupation, which was linked with a job-exposure matrix to categorize EMF exposure into three, broad categories. In the overall twin population, EMF exposure was not associated with either dementia or Alzheimer's disease. An association with EMF was observed for those employed in manual labor and for those with early onset dementia (≤ 75 years at diagnosis), but not Alzheimer's disease. This study's strength is the recruitment of living cases; however, small numbers limited the subgroup analyses and robust associations were not found.

In summary, two cohort studies of the Swiss population of relatively high quality were followed for death due to neurodegenerative disease. Röösli et al. (2007b) reported an association between Alzheimer's disease or senile dementia and occupational magnetic-field exposure, while Huss et al. (2009) reported an association between Alzheimer's disease or senile dementia and living within 50 m of a high-voltage transmission line for at least 15 years. Neither study reported an association with any other neurodegenerative disease, including ALS. A cohort of utility workers, however, did not confirm an association with Alzheimer's disease mortality and magnetic field exposure. The meta-analysis and supporting evaluation of study quality by García, Santibáñez, and colleagues confirmed that the associations reported in previous occupational studies are highly inconsistent and the studies have many limitations (Santibáñez et al., 2007; García et al., 2008).

The main limitations of these studies include the difficulty in diagnosing Alzheimer's disease; the difficulty of identifying a relevant exposure window given the long and nebulous course of this disease; the difficulty of estimating magnetic field exposure prior to the appearance of the disease; the under-reporting of Alzheimer's disease on death certificates; crude exposure evaluations that are often based on the recollection of occupational histories by friends and family given the cognitive impairment of the study participants; and the lack of consideration of both residential and occupational exposures or confounding variables.

The recent epidemiologic studies do not alter the conclusion that there is inadequate data on Alzheimer's disease or ALS. While a good number of studies have been published since the WHO review, little progress has been made on clarifying these associations. Further research is still required, particularly on electrical occupations and ALS (Kheifets et al., 2008). There is currently no body of *in vivo* research to suggest an effect and two studies reported no effect of magnetic fields on ALS progression (Seyhan and Canseven, 2006; Poulletier de Gannes et al., 2008). These conclusions are consistent with the recent review by the SCENIHR (SCENIHR, 2009).

Table 8. Relevant studies of neurodegenerative disease published after the WHO review

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
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
García, et al.	2008	Occupational exposure to extremely low frequency electric and magnetic fields and Alzheimer disease: a meta-analysis
Huss, et al.	2009	Residence near power lines and mortality from neurodegenerative diseases: longitudinal study of the Swiss population
Poulletier de Gannes et al.	2008	Amyotrophic lateral sclerosis (ALS) and extremely-low frequency (ELF) magnetic fields: a study in the SOD-1 transgenic mouse model
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
Seidler et al.	2007	Occupational exposure to low frequency magnetic fields and dementia: a case-control study
Seyhan and Canseven	2006	In vivo effects of ELF MFs on collagen synthesis, free radical processes, natural antioxidant system, respiratory burst system, immune system activities, and electrolytes in the skin, plasma, spleen, lung, kidney, and brain tissues
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

3 Other Areas of Research

Pacemakers and implanted cardiac devices

The sensing system of pacemakers and other implanted cardiac devices (ICD) is designed to be responsive to the heart's electrical signal. For this reason, other electrical signals potentially can interfere with the normal functioning of pacemakers and ICDs, a phenomenon called electromagnetic interference (EMI). Most sources of EMF are too weak to affect a pacemaker or ICD; however, EMF from certain sources, e.g., some appliances and industrial equipment, may cause interference. This section considers potential EMI with implanted cardiac devices such as pacemakers and defibrillators.

In the presence of electromagnetic fields, pacemakers and ICDs can respond in different ways, defined as modes. The probability of interference occurring and the mode of the response depend on the strength of the interference signal, the patient's orientation in the electromagnetic field, the exact location of the device, and the variable parameters of the device that are specific to a patient.

There are a number of experimental studies dating back to the 1990s that were conducted to assess whether interference may occur when currents are induced in the patient's body by electric or magnetic fields (e.g., Toivonen et al., 1991; Astridge et al., 1993; Scholten and Silny, 2001). In general, pacing abnormalities in these tests occurred at magnetic field levels that are much higher than the levels a person would encounter on a daily basis. Electric fields did produce interference at levels that can be produced by certain electrical sources, but most pacemakers were not affected by high levels of electric fields (up to 20 kV/m) and did not exhibit any pacing abnormalities. Unipolar (single lead) pacemakers tended to be more sensitive to electric fields compared to bipolar (two lead) devices, which are designed specifically to reduce the effects of EMI.

A recent study by Joosten et al. (2009) confirmed earlier work by Scholten and Silny (2001). Both studies found that the performance of a pacemaker in the presence of external ELF electric fields varied considerably based on anatomical and physiological conditions. The 15 study

subjects in Joosten et al. experienced a variance of up to 200% when the interference voltage was applied at the input of their cardiac pacemakers. This variance was due to individual, personal factors such as state of respiration, systole and diastole of the heart, filling of the stomach, and muscle activity. The authors' analyses further suggested that for a 50-Hz electric field to affect the function of the most sensitive unipolar pacemaker, the field levels would have to be between 4.3 kV/m and 6.2 kV/m. Unipolar pacemakers are less and less common today; the study authors found that in Germany, only 6% of the pacemakers in use have a unipolar sensing system.

Suggested exposure levels have been determined by the American Conference of Governmental Industrial Hygienists (ACGIH) and the Electric Power Research Institute (EPRI) to prevent against pacemaker EMI. Both organizations suggest that exposures be kept below 1.5-2 kV/m for electric fields and the ACGIH recommends an exposure level not to exceed 1 G for magnetic fields (ACGIH 2001, EPRI 2004). These recommendations are general in nature and do not address that classes of pacemakers from some manufacturers are quite immune to interference even at levels much greater than these recommended guidelines. Both the ACGIH and EPRI recommend that patients consult their physicians and the respective pacemaker manufacturers before following these organizations' guidelines.

In addition, the Food and Drug Administration's Center for Devices and Radiological Health has issued guidelines for both the development of pacemakers and the design of new electrical devices to minimize susceptibility to electrical interference from any source. Pacemakers are designed to filter out electrical stimuli from sources other than the heart, e.g., the muscles of the chest, currents encountered from touching household appliances, or currents induced by external electric or magnetic fields. Used in both temporary and permanent pacemakers, these electrical filters increase the pacemaker's ability to distinguish extraneous signals from legitimate cardiac signals (Toivonen et al., 1991). Furthermore, most circuitry of modern pacemakers is encapsulated by titanium metal, which insulates the device by shielding the pacemaker's pulse generator from electric fields. Some pacemakers also may be programmed to pace the heart automatically if interference from electric or magnetic fields is detected (fixed pacing mode). This supports cardiac function and allows the subject to feel the pacing and move away from the source.

Due to recent design improvements, many pacemakers currently in use would not be susceptible to low intensity electric fields. There remains a very small possibility that some pacemakers, particularly those of older design and with single-lead electrodes, may sense potentials induced on the electrodes and leads of the pacemaker and provide unnecessary stimulation to the heart.

In summary, interference from strong electric fields is theoretically possible under certain circumstances. The likelihood of interference occurring is low, however, particularly with respect to sources that produce low levels of electric fields and when modern devices are implanted. It is recommended that concerned patients contact their doctors to discuss the make and model of their implanted device, their clinical condition, and any lifestyle factors that put them in close contact with strong electric or magnetic fields.

Flora

Electric currents are involved in cell to cell communication in plants (Framm and Lautner, 2007). For this reason, numerous laboratory and on-site studies over the past 35 years have been conducted to assess the possible effects of exposure to ELF EMF from transmission lines on flora—including agricultural crops, trees, and forest and woodland vegetation (e.g., Hodges et al., 1975; Bankoske et al., 1976; McKee et al., 1978; Miller et al., 1979; Rogers et al., 1980; Lee and Clark, 1981; Warren et al., 1981; Rogers et al., 1982; Greene 1983; Hilson et al., 1983; Hodges and Mitchell, 1984; Brulfert et al., 1985; Parsch and Norman, 1986; Conti et al., 1989; Krizaj and Valencic 1989; Ruzic et al., 1992; Reed et al., 1993; Smith et al., 1993; Mihai et al., 1994; Davies 1996; Zapotosky et al., 1996). Researchers have found no adverse effects on plant responses from exposure to EMF levels comparable to that produced by high-voltage transmission lines, including seed germination, seedling emergence and growth, leaf area per plant, flowering, seed production, longevity, and biomass production. The one confirmed adverse effect was damage to the tops of trees growing under or within 40 feet of an *experimental* transmission line operating at a voltage of 1,200 kV, attributable to corona-induced damage to branch tips. The right-of-way (ROW) clearance on *operational* transmission lines is typically a 100 to 200 foot clearance on each side of the line; this area would be cleared of trees or the branches trimmed back sufficiently to prevent flashover and other interference. This effect is not relevant to trees growing at greater distances from the ROW clearance area.

Experimental studies of plants have suggested that magnetic fields increased plant size and weight for radish and barley but not mustard plants (Davies, 1996). Two more recent studies on the possible effects of EMF on plants were performed by Huang and Wang (2008) and Costanzo (2008). Huang and Wang evaluated the effects of magnetic fields induced on the early seed germination of mung beans. The exposures from an inverter system were applied at six different frequencies between 10 Hz and 60 Hz, producing magnetic-field levels from 6 mG to 20 mG. The authors found that magnetic-field exposure at frequencies of 20 and 60 Hz enhanced early mung bean growth, while magnetic fields induced by 10, 30, 40, and 50 Hz frequencies had an inhibitory effect on early mung bean growth. Costanzo (2008) performed a similar study of soy beans exposed *in vitro* to 50-Hz electric fields at strengths of 1.3 kV/m and 2.5 kV/m (root mean square). The author found that this exposure increased soy bean growth in length. In addition, this same study reported that direct current (DC) electric fields of the same peak to peak value had no effect (Costanzo, 2008).

Thus, researchers have found no adverse effects on plant responses at the levels of EMF produced by typical high- or low-voltage transmission lines.

Fauna

Since the 1970s, research has been conducted on the possible effect of EMF on wild and domestic animals in response to concerns about the effects of high-voltage and ultra-high-voltage transmission lines in the vicinity of farms and the natural habitat of wild animals. National agencies and universities have conducted research on an assortment of fauna using a variety of study designs including observational studies of animals in their natural habitats and highly-controlled experimental studies. The research to date does not suggest that AC magnetic or electric fields (or any other aspect of high-voltage transmission lines, such as audible noise) result in adverse effects on the health, behavior, or productivity of fauna, including livestock (e.g., dairy cows, sheep, and pigs) and a variety of other species (e.g., small mammals, deer, elk, birds, and bees).

Dairy Cattle and Deer

Burchard et al. (2007) is the most recent publication in a long-term series of controlled studies conducted at McGill University (e.g., Rodriquez et al., 2002, 2003, 2004; Burchard et al., 2003; 2004) on the possible effects of strong and continuous EMF exposure on the health, behavior, and productivity of dairy cattle. The broad goal of this research program was to assess whether EMF exposure could mimic the effect of days with long periods of light and increase milk production and feed intake through a hormonal pathway involving melatonin. In previous studies, some differences were reported between EMF-exposed and unexposed cows; however, they were not reported consistently between studies, the changes were still within the range of what is considered normal, and it did not appear that the changes were adverse in nature.

The study by Burchard et al. in 2007 differed from previous studies in that the exposure was restricted to magnetic fields; the outcomes evaluated included the hormones progesterone, melatonin, prolactin, and insulin-like growth factor 1 (IGF-1), as well as feed consumption. No significant differences in melatonin levels, progesterone levels, or feed intake were reported. Significant decreases in prolactin and IGF-1 levels were reported. Thus, similar to the previous studies by this group of investigators, Burchard et al. (2007) did not report findings that suggest magnetic fields cause changes in the melatonin pathway that could result in effects on reproduction or milk production.

The research does indicate that some species of animals are able to detect and orient to DC magnetic fields at levels associated with the earth's static geomagnetic field (~ 500 mG), and this detection may be important for navigational purposes (in particular for species such as birds). Based upon the characteristics of the major hypothesized detection mechanisms and testing in some species, it seems unlikely that a weak 60-Hz magnetic field would be detected or that it would perturb navigational functions.

Along these lines, two studies, both of which received considerable press attention, published analyses of the orientation of cattle and deer using satellite images and field observations that identify a possible geomagnetic component influencing the animals' behavior. A report by Begall et al. (2008) found that domestic cattle and red and roe deer tend to orient their bodies pointing in a northerly direction. The authors' hypothesize that this body orientation is related

to the earth's static geomagnetic field because in areas where the earth's magnetic North Pole can be distinguished more easily from the geographic North Pole's high magnetic declination, body orientation appeared to point more towards the magnetic north rather than the geographic north. This northerly body orientation was not correlated with time of day or the position of the sun, and although the authors speculated that the orientation of the animals was not influenced by wind, no analyses were presented. Based on these limited and indirect data the authors raised the possibility that these species can detect the earth's geomagnetic field.

In the second study, Burda et al. (2009) also explored the possible magnetic basis for the northerly orientation of cattle and deer by analyzing their behavior in the vicinity of high-voltage power lines. They report that cattle within 150 m and deer within 50 m of high-voltage power lines exhibit a random body orientation with respect to magnetic north. Some of the effect might be attributed to the deflection of the geomagnetic field by steel towers close to the line, but the authors did not test this possibility. Other analyses indicated that the orientation of cattle differed around power lines running in an east-west or north-south direction, which suggests that neither sun nor wind cues explain the orientation of these animals with respect to magnetic north. If the observed orientations of cattle and deer are attributable to the earth's geomagnetic field, the biological significance is not clear and the authors suggest additional experimental study. With respect to deer, the authors commented that deer prefer to locate near power lines, perhaps because of the browse or shelter afforded.

Wild Bees and Honey Bees

Wild bees have an important role in natural plant and forest ecosystems. Research on wild bees was conducted at a site near a United States Navy communications system in Northern Michigan where two species of honeybees were observed living in the vicinity of this facility. The researchers studied the bees' exposure to 76-Hz electric and magnetic fields produced by the facility's communications system and compared the mortality, foraging behavior, and nest architecture to a group of honeybees living at a distance from the facility. A few differences were found in nesting parameters, although the effects were small, inconsistent, and likely due to other factors. Although a small increase in the overwinter mortality was reported in one of the two species studied, the researchers concluded that since the reported differences were small

and inconsistent between experiments, there were no findings that raised concern about ELF EMF exposures to wild bees (Zapotosky et al., 1996). This conclusion was confirmed in a review by the United States National Academy of Sciences (NAS, 1997).

More research has focused on commercial honeybees since farmers often place hives on fields near transmission lines. Greenberg et al. (1981) studied the effect of a 765-kV transmission line on honeybee colonies placed at varying distances from the transmission line's centerline, with some hives exposed to EMF from the line and some shielded. Differences between the shielded and unshielded hives were reported at exposures above 4.1 kV/m, including decreases in hive weight, abnormal amounts of propolis at hive entrances, increased mortality and irritability, loss of the queen in some hives, and a decrease in the hive's overwinter survival.

These adverse effects were reported only in the unshielded group. Since the shielding only prevented exposure to electric fields, not magnetic fields, the results indicate that these adverse effects are attributable to electric field exposure. These results have been replicated by other investigators (Rogers et al., 1980, 1981, 1982). Further studies indicated that the effects were indirect, i.e., the electric fields were not affecting the bees directly, and that field levels greater than 200 kV/m were required to affect the behavior of free-flying bees. Thus, heating of the hive by induced currents caused some of the adverse effects and the rest were attributed to shocks within the hive (Bindokas et al., 1988a, 1988b, 1989). Prevention is easily accomplished by placing a grounded metal cover on top of the hive.

Since the nests of wild bees in the ground or in trees contain no metal or highly conductive materials, there appears to be little relevance of such effects to wild bees. At these locations, wild bees also are naturally shielded from electric fields. Laboratory studies indicate that bees are unable to discriminate 60-Hz magnetic fields reliably at intensities less than 4,300 mG, although they can detect fluctuations in the earth's static geomagnetic field as weak as 0.26 mG (Kirschvink et al., 1997). The difference in the sensitivity of honey bees is an illustration that a sensory mechanism has developed to detect static magnetic fields that effectively rejects extraneous signals, in this case AC (60-Hz) magnetic fields.

Birds

A recent study by Dell'omo et al. (2009) analyzed the effects of exposure to magnetic fields from high-voltage power lines during the embryonic and post-hatching period of kestrel nestling. The authors found that exposure does not have any significant short-term physiological effects on these birds.

The ability of birds to detect and use of the earth's geomagnetic field during migration does not translate to a capability to detect 60-Hz magnetic fields. Scientists have hypothesized that the mechanism for detection of the earth's geomagnetic field by birds (and bees), for which there is the most evidence, indicates they would be far less sensitive to 60-Hz magnetic fields. The WHO suggested that power frequency fields at intensities much less than the earth's geomagnetic field of around 500 mG are unlikely to be of much biological significance in relation to birds' navigational abilities because the changes produced by ELF magnetic fields and static magnetic fields are similar (WHO, 2007).

Finally, in a study by Elmusharaf et al. (2007), veterinarians in the Netherlands noted the beneficial effects of AC magnetic fields in poultry. The researchers infected broiler chickens with coccidiosis and reported that exposure to a 50 mG AC magnetic field for 30 minutes each day for a course of 15 days prior to infection provided significant protection against intestinal lesions and reduced growth characteristic of this disease.

Overall, the research over the course of the past 35 to 40 years does not suggest that electric or magnetic fields result in any adverse effects on the health, behavior, or productivity of fauna, including livestock, small mammals, deer, elk, birds, and bees.

Marine Life

Although transmission lines mostly traverse the land they also frequently cross water bodies as well. Therefore, the potential for effects on certain marine ecological systems are evaluated regarding the potential impact of EMF on aquatic species in rivers and creeks. To date, there is little or no evidence that fish, mammals, or birds exhibit any harmful effects when exposed to EMF of frequencies close to or at power frequencies (50-60 Hz) at levels found under

transmission lines, even for a prolonged period of time (e.g., NRC, 1997a, 1997b; NIEHS 1998; WHO, 2007a). Thus, there is no concern that EMF would have any direct toxic effects on the marine biota.

A number of fish species, however, are reported to make use of the earth's geomagnetic field in navigation and migration, including Pacific salmon (*Oncorhynchus spp.*); the chinook salmon (*O. tschawytscha*) and the steelhead (*O. mykiss*) species particularly spend their adult lives in estuarine or oceanic environments and are well known for their annual spawning runs into freshwater, returning to the home streams and rivers where they were spawned and spent the first few months of their lives (Groot and Margolis, 1998). Pacific salmon are an important part of the history, ecology, and economy of the Pacific Northwest region.

Transmission lines will be a source of potential exposure to 60-Hz magnetic fields in rivers and streams below the conductors, but not electric field exposure because the water shields the fish from electric fields. Since the level of EMF decreases with distance from the source, maximum magnetic-field exposures of fish will occur when they are directly under the lines. The magnetic field levels in rivers and streams below transmission lines would be expected to be significantly lower than for spans on land because clearances for river and stream crossings are usually much higher. Additionally, prolonged exposure is not a critical issue as the fish species of most interest are migratory by nature and will only be exposed to magnetic fields during the relatively short time they take to spawn or travel down or up the river during their life cycle.

The Pacific salmon have been thought to navigate by several mechanisms: detecting and orienting to the earth's geomagnetic field, using a celestial compass (i.e., based on the position of the sun in the sky), and using their innate ability to imprint on their home stream by odor (Groot and Margolis, 1998, Quinn et al, 1981).

Generally, scientific studies have reported that, along with other cues or biological mechanisms, certain species of birds, bees, and fish may have magnetite in certain organs in their bodies, and use magnetite crystals as an aid in navigation (Bullock, 1977; Wiltschko and Wiltschko, 1991, Kirschvink et al, 1993, Walker et al. 1988). Crystals of magnetite have been found in Pacific salmon (Mann et al, 1998; Walker et al, 1998). These magnetite crystals are believed to serve as a compass that orients to the earth's magnetic field. Other studies, however, have not found

magnetite in sockeye salmon (*Oncorhynchus nerka*) fry (Quinn et al., 1981). While salmon can apparently detect the geomagnetic field, their behavior is governed by multiple stimuli as demonstrated by the ineffectiveness of magnetic field stimuli in the daytime (Quinn et al., 1982) and the inability of strong magnetic fields from permanent magnets attached to sockeye salmon (Ueda et al., 1998) or other salmon (Yano et al., 1997) to alter their migration behavior.

An important consideration is that the earth's geomagnetic field is static (0 Hz), in contrast to the oscillating magnetic field created by AC transmission lines, which produce current that changes direction and intensity 60 times per second. Static magnetic fields have fixed polarity, i.e. the earth's magnetic north and south poles. AC transmission lines produce magnetic fields that do not have fixed polarity.

No studies have been conducted to date that specifically examine the effects of AC magnetic fields on the salmon's ability to orient to the earth's geomagnetic field. Theoretical calculations do not suggest that 60-Hz magnetic fields could affect magnetite at levels less than 50 mG (Adair 1994). Studies on the response of other organisms that also use magnetite crystals as one means of navigation can, however, provide useful insight regarding salmon. Kirschvink et al. (1993) reports studies of the effects of AC magnetic fields on honey bees, which use magnetite crystals to navigate. In this study, the honey bees only oriented to an AC magnetic field when it was one million times greater in intensity than the DC field needed to elicit the same orientation response. This difference in intensity indicates that the AC magnetic field is less influential than the DC magnetic field in the navigation of honey bees and potentially other organisms that orient to the earth's geomagnetic field using magnetite crystals (Kirschvink et al., 1993). The level of AC magnetic fields under transmission lines are well below the levels reported in that study.

The scientific literature does not support the conclusion that the EMF associated with the proposed transmission line will have an adverse impact on the survival, growth, and reproduction of organisms in a marine ecosystem. There are no data on the effects of AC EMF on salmon navigation, but based on a study with honey bees, it appears that organisms that use magnetite crystals to orient to the earth's geomagnetic field would be affected only when the field levels are very much greater than the levels expected from a transmission line. Given this

evidence and the salmon's ability to navigate using multiple sensory cues, overhead transmission lines are unlikely to have an adverse impact on these species of interest and the aquatic ecosystems of these creeks.

4 Standards and Guidelines

Scientific agencies develop exposure standards and guidelines to protect against known health effects following a thorough review of the relevant research. One of the main objectives of weight-of-evidence reviews is to identify the lowest exposure level below which no health hazards have been found (i.e., a threshold level). Exposure limits are then set *well below* the threshold level established by these reviews to take into account individual variability and sensitivity that may exist in susceptible populations.

The only effects known to be produced in humans by exposure to ELF EMF are seen at very high field levels to which the average person is not typically exposed. The effects are short-term, immediate, perceptible reactions to the electrical stimulation of the muscle and the nervous system. These effects are neither severe nor life-threatening.

Two international scientific organizations, ICNIRP and ICES, have published guidelines for limiting public exposure to ELF EMF to protect against these effects (ICNIRP, 1998, 2010; ICES, 2002). 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 is the formally recognized, non-governmental organization that develops safety guidance for non-ionizing radiation for the WHO, the International Labour Organization, and the European Union.

The ICES is sponsored by the American National Standards Institute and IEEE. The mandate for ICES is the "Development of standards for the safe use of electromagnetic energy in the range of 0 Hz to 300 GHz relative to the hazards of exposure to man … to such energy."[25] The ICES encourages a balanced international volunteer participation from several sectors: the interested general public; the scientific, health and engineering communities; agencies of governments; energy producers; and energy users.

[25] The ICES is a 50-year-old internationally recognized, EMF standard-setting organization, which is sponsored by the IEEE that itself was established in 1884. The ICES should not be confused with a group of scientists who have acted together as an advocacy group and banded together under the similar name of the International Commission for Electromagnetic Safety in 2003.

Although both organizations have the same objectives and use similar methods, their recommended exposure limits to 60-Hz EMF for the general public differ (Table 9). The ICNIRP recommends screening values for magnetic fields of 833 mG for the general public and 4,200 mG for workers (ICNIRP, 1998). The ICES recommends maximum permissible exposure of 9,040 mG for magnetic fields (ICES, 2002). The ICNIRP's screening value for exposure to 60-Hz electric fields for the general public is 4.2 kV/m and the ICES screening value is 5 kV/m. Both organizations allow higher exposures if it can be demonstrated that exposures do not produce current densities or electric fields within tissues that exceed basic restrictions on internal current densities or electric fields.

Table 9. Reference levels for whole body exposure to 60-Hz fields: general public

Organization recommending limit	Magnetic fields	Electric fields
ICNIRP restriction level	833 mG	4.2 kV/m
ICES maximum permissible exposure (MPE)	9,040 mG	5 kV/m 10 kV/m[a]

[a] This is an exception within transmission line ROWs because people do not spend a substantial amount of time in ROWs and very specific conditions are needed before a response is likely to occur (i.e., a person must be well insulated from ground and must contact a grounded conductor) (ICES, 2002, p. 27).

These guidelines were developed following a weight-of-evidence review of the literature by each organization, including epidemiologic and experimental evidence related to both short-term and long-term exposure. Both reviews concluded that the stimulation of nerves and the central nervous system could occur at very high exposure levels immediately upon exposure. While ICNIRP and ICES reference levels for electric fields are similar, the reference levels for magnetic fields differ by a factor of 10. As explained by Reilly (2005), this difference results from the way the two guidelines have extrapolated responses of the retina of the eye to magnetic fields at around 20 Hz to higher frequencies and other tissues. Their reviews also concluded that there was not sufficient evidence to support a causal role for EMF in the development of cancer or other long-term adverse health effects. Therefore, neither organization found a basis to recommend quantitative exposure guidelines to prevent effects at lower exposure levels.

Following the publication of their 1998 guidelines, the ICNIRP published an evaluation of the epidemiologic literature (ICNIRP, 2001) and a full weight-of-evidence evaluation of health

research on EMF (ICNIRP, 2003), concluding again that there is no basis for exposure restrictions for long-term health effects. In June 2009, the ICNIRP published an updated review of the scientific literature related to potential short- and long-term adverse effects, and *draft* guidelines to replace their 1998 ELF EMF exposure guidelines (ICNIRP, 2009). The document recommended no changes to the screening values shown in Table 9, nor did the final standard that was published in December 2010. .

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

5 References

Abdul Rahman HI, Shah SA, Alias H, Ibrahim HM. A case-control study on the association between environmental factors and the occurrence of acute leukemia among children in Klang Valley, Malaysia. Asian Pac J Cancer Prev 9:649-652, 2008.

Adair RK. Constraints of thermal noise on the effects of weak 60-Hz magnetic fields acting on biological magnetite. Proc Natl Acad Sci U S A. 91:2925–2929, 1994.

Ahlbom A, Day N, Feychting M, Roman E, Skinner J, Dockerty J, Linet M, Michealis J, Olsen JH, Tynes T, Verkasalo PK. A pooled analysis of magnetic fields and childhood leukemia. Br J Cancer 83:692-698, 2000.

Aksen F, Adkag MZ, Ketani A, Yokus B, Kaya A, Dasdag S. Effect of 50-Hz 1-mT magnetic field on the uterus and ovaries of rats (electron microscopy evaluation). Med Sci Monit 12:BR215-220, 2006.

Al-Akhras MA, Darmani H, Elbetieha A. Influence of 50 Hz magnetic field on sex hormones and other fertility parameters of adult male rats. Bioelectromagnetics 27:127-31, 2006.

Al-Akras MA. Influence of 50 Hz magnetic field on sex hormones and body, uterine, and ovarian weights of adult female rats. Electromagnetic Biology and Medicine 27:155-163, 2008.

American Conference of Government Industrial Hygienists (ACGIH). Documentation of the Threshold Limit Values and Biological Exposure Indices, 7th edition. Publication No. 0100. Cincinnati, OH: American Conference of Government Industrial Hygienists, 2001.

Andel R, Crowe M, Feychting M, Pedersen NL, Fratiglioni L, Johansson B, Gatz M. Work-related exposure to extremely low-frequency magnetic fields and dementia: results from the population-based study of dementia in Swedish twins. Journal of Gerontology [E-Pub ahead of print], 2010.

Anderson LE, Boorman GA, Morris JE, Sasser LB, Mann PC, Grumbein SL, Hailey JR, McNally A, Sills RC, Haseman JK. Effect of 13 week magnetic field exposures on DMBA-initiated mammary gland carcinomas in female Sprague-Dawley rats. Carcinogenesis 20:1615-1620, 1999.

Anselmo CW, Santos AA, Freire CM, Ferreira LM, Cabral Filho JE, Catanho MT, and Medeiros Mdo C. Influence of a 60 Hz, 3 microT, electromagnetic field on the reflex maturation of Wistar rats offspring from mothers fed a regional basic diet during pregnancy. Nutr Neurosci 9:201-6, 2006.

Anselmo CS, Silva TL, Holanda TG, Prado LV, Cabral-Filho JE, Catanho MT, Medeiros MC. Influence of a 60 Hz, microT, electromagnetic field on the somatic maturation of wistar rat offspring fed a regional basic diet during pregnancy. Braz J Biol 68:641-648, 2008.

Astridge PS, Kaye GC, Whitworth S, Kelly P, Camm AJ, Perrins EJ. The response of implanted dual chamber pacemakers to 50 Hz extraneous electrical interference. Pacing Clin Electrophysiol 16:1966-1974, 1993.

Auger N, Joseph D, Goneau M, Daniel M. The relationship between residential proximity to extremely low frequency power transmission lines and adverse birth outcomes. J Epidemiol Community Heath [E-Pub ahead of print], 2010.

Australian Centre for Radiofrequency Bioeffects Research (ACRBR). ACRBR Position Statement on BioInitiative Report. December 18, 2008. http://www.acrbr.org.au/FAQ/ACRBR%20Bioinitiative%20Report%2018%20Dec%202008.pdf

Aydin M, Cevik A, Kandemir FM, Yuksel M, and Apaydin AM. Evaluation of hormonal change, biochemical parameters, and histopathological status of uterus in rats exposed to 50-Hz electromagnetic field. Toxicology and Industrial Health 25:352-158, 2009.

Bankoske JW. The effects of high voltage electric fields on the growth and development of plants and animals. Proceedings of the First National Symposium on Environmental Concerns in Rights-of-Way Management at Mississippi State University, pp. 112-123, 1976.

Baum A, Mevissen M, Kamino K, Mohr U, Löscher W. A histopathological study on alterations in DMBA-induced mammary carcinogenesis in rats with 50 Hz, 100 muT magnetic field exposure. Carcinogenesis 16:119-125, 1995.

Begall S, Červený J, Neef J, Voljtěch O, Burda H. Magnetic alignment in grazing and resting cattle and deer. PNAS 105:13451-13455.

Bernabò N, Tettamanti E, Pistilli MG, Nardinocchi D, Berardinelli P, Mattioli M, Barboni B. Effects of 50 Hz extremely low frequency magnetic field on the morphology and function of boar spermatozoa capacitation in vitro. Theriogenology 67:801-815, 2007.

Bernard N, Alberdi AJ, Tanguy ML, Brugere H, Helissey P, Hubert C, Gendrey N, Guillosson JJ, Nafziger J. Assessing the potential Leukemogenic effects of 50 Hz and their harmonics using an animal leukemia model. Journal of Radiation Research 49:565-577, 2008.

Bindokas VP, Gauger JR, Greenberg B. Exposure scheme separates effects of electric shock and electric field for honey bees, *Apis mellifera, L.* Bioelectromagnetics 9:275-284, 1988a.

Bindokas VP, Gauger JR, Greenberg B. Mechanism of biological effects observed in honey bees (*Apis mellifera, L.)* hived under extra-high-voltage transmission lines: implications derived from bee exposure to simulated intense electric fields and shocks. Bioelectromagnetics 9:285-301, 1988b.

Bindokas VP, Gauger JR, Greenberg B. Laboratory investigations of the electrical characteristics of honey bees and their exposure to intense electric fields. Bioelectromagnetics 10:1-12, 1989.

Boorman GA, Anderson LE, Morris JE, Sasser LB, Mann PC, Grumbein SL, Hailey JR, McNally A, Sills RC, Haseman JK. Effects of 26-week magnetic field exposure in a DMBA initiation-promotion mammary glands model in Sprague-Dawley rats. Carcinogenesis 20:899-904, 1999a.

Boorman GA, McCormick DL, Findlay JC, Hailey JR, Gauger JR, Johnson TR, Kovatch RM, Sills RC, Haseman JK. Chronic toxicity/oncogenicity evaluation of 60 Hz (power frequency) magnetic fields in F344/N rats. Toxicologic Pathology 27:267-78, 1999b.

Brulfert A, Miller MW, Robertson D, Dooley DA, Economou P. A cytohistological analysis of roots whose growth is affected by a 60-Hz electric field. Bioelectromagnetics. 6:283-291, 1985.

Bullock TH. Electromagnetic sensing in fish. Neurosciences Res Prog Bull 15:17-12, 1977.

Burchard JF, Monardes H, Nguyen DH. Effect of 10 kV, 30 mT, 60 Hz electric and magnetic fields on milk production and feed intake in nonpregnant dairy cattle. Bioelectromagnetics 24:557-563, 2003.

Burchard JF, Nguyen DH, Monardes HG, Petitclerc D. Lack of effect of 10 kV/m 60 Hz electric field exposure on pregnant dairy heifer hormones. Bioelectromagnetics 25:308-312, 2004.

Burchard JF, Nguyen DH, Monardes HG. Exposure of pregnant dairy heifer to magnetic fields at 60 Hz and 30 uT. Bioelectromagnetics 28:471-476, 2007.

Burda H, Begall S, Červený J, Neef J, Němec, P. Extremely low-frequency electromagnetic fields disrupt magnetic alignment of ruminants. PNAS 106:5708-5713, 2009.

Burdak-Rothkamm S, Rothkamm K, Folkard M, Patel G, Hone P, Lloyd D, Ainsbury L, Prise KM. DNA and chromosomal damage in response to intermittent extremely low frequency magnetic fields. Mutation Research 672:82-89, 2009.

Chen C, Ma X, Zhong M, Yu Z. Extremely low frequency electromagnetic fields exposure and female breast cancer risk: a meta-analysis based 24,338 cases and 60,628 controls. Breast Cancer Res Treat 2010 Feb 10 [Epub ahead of print].

Chung M-K, Kim Y-B, Ha C-S, Myung S-H. Lack of a co-promotion effect of 60 Hz rotating magnetic fields on n-ethyl-n-nitrosourea induced neurogenic tumors in F344 rats. Bioelectromagnetics 29:539-48, 2008.

Coble JB, Dosemeci M, Stewart PA, Blair A, Bowman J, Fine HA, Shapiro WR, Selker RG, Loeffler JS, Black PM, Linet MS, Inskip PD. Occupational exposure to magnetic fields and the risk of brain tumors. Neuro Oncol 11:242-249, 2009.

Conti R, Nicolini P, Cerretelli P, Maronato V, Veicsteinas A, Floris C. Enel's research activity on possible biological effects of 50 Hz electromagnetic fields – results and plans of a large research programme. Alta Frequenza 58:395-378, 1989.

Costanzo E. The influence of an electric field on the growth of soy seedlings. Journal of Electrostatics 66:417-420, 2008.

Davanipour Z, Tseng CC, Lee PJ, Sobel E. A case-control study of occupational magnetic field exposure and Alzheimer's disease: results from the California Alzheimer's Disease Diagnosis and Treatment Centers. BMC Neurol 7:13, 2007.

Davanipour Z and Sobel E. Long-term exposure to magnetic fields and the risk of Alzheimer's disease and breast cancer: Further biological research. Pathophysiology 16:149-156, 2009.

Davies MS. Effects of 60 Hz electromagnetic fields on early growth in three plant species and a replication of previous results. Bioelectromagnetics 17:154-161, 1996.

De Bruyn L and De Jager L. Effect of long-term exposure to a randomly varied 5 Hz power frequency magnetic field on the fertility of the mouse. Electromagnetic Biology and Medicine 29:52-61, 2010.

Dell'omo G, Costantini D, Lucini V, Antonucci G, Nonno R, Polichetti A. Magnetic fields produced by power lines do not affect growth, serum melatonin, leukocytes and fledging success in wild kestrels. Comp Biochem Physiol Toxicol Pharmacol 150:372-376, 2009.

Draper G, Vincent T, Kroll ME, Swanson J. Childhood cancer in relation to distance from high voltage power lines in England and Wales: a case-control study. BMJ 330:1290, 2005.

Dundar B, Cesur G, Comlekci S, Songur A, Gokcimen A, Sahin O, Ulukut O, Yilmaz HR, Sutcu R, Caliskan S. The effect of the prenatal and post-natal long-term exposure to 50 Hz electric field on growth, pubertal development and IGF-1 levels in female Wistar rats. Toxicology and Industrial Health 25:479-487, 2009.

Electric Power Research Institute (EPRI). Electromagnetic Interference With Implanted Medical Devices: 1997-2003. Report No.1005570, 2004. A summary can be found at: http://my.epri.com/portal/server.pt?space=CommunityPage&cached=true&parentname=ObjMgr&parentid=2&control=SetCommunity&CommunityID=221&PageIDqueryComId=0

Elmusharaf MA, Cuppen JJ, Grooten NA, Beynen AC. Antagonistic effect of electromagnetic field exposure on coccidiosis infection in broiler chickens. Poultry Science 86:2139-2143, 2007.

Elwood JM. Childhood leukemia and residential magnetic fields: are pooled analyses more valid than the original studies? Bioelectromagnetics 27:112-118, 2006.

Fadel RAR, Salem A-H, Ali MH, Abu-Saif AN. Growth assessment of children exposed to low frequency electromagnetic fields at the Abu Sultan area in Ismailia (Egypt). Antrop Anz 64:211-226, 2006.

Farkhad SA, Zare S, Hayatgeibi H, Qadiri A. Effects of extremely low frequency electromagnetic fields on testes in guinea pig. Pakistan Journal of Biological Sciences 10:4519-4522, 2007.

Federal-Provincial-Territorial Radiation Protection Committee (FPTRPC). Heath Effects and Exposure Guidelines Related to Extremely Low Frequency Electric and Magnetic Fields - An Overview. Prepared by The ELF Working Group, 2005.

Fedrowitz M, Kamino K, Löscher W. Significant differences in the effects of magnetic field exposure on 7,12-dimethylbenz(a)anthracene-induced mammary carcinogenesis in two substrains of Sprague-Dawley rats. Cancer Res 64:243-251, 2004.

Fedrowitz M and Löscher W. Exposure of Fischer 344 rats to a weak power frequency magnetic field facilitates mammary tumorigenesis in the DMBA model of breast cancer. Carcinogenesis 29:186-193, 2008.

Feizi AA and Arabi MA. Acute childhood leukemias and exposure to magnetic fields generated by high voltage overhead power lines – a risk factor in Iran. Asian Pac J Cancer Prev 8:69-72, 2007.

Feychting M, Jonsson F, Pedersen NL, Ahlbom A. Occupational magnetic field exposure and neurodegenerative disease. Epidemiology 14:413-419, 2003.

Florida Department of Environmental Regulation (FDER). Electric and Magnetic fields. Chapter 17-274. Department of Environmental Regulation Rules, March, 1989.

Florida Department of Environmental Protection (FDEP). Chapter 62-814 Electric and Magnetic Fields, 1996.

Foliart DE, Pollock BH, Mezei G, Iriye R, Silva JM, Ebi KL, Kheifets L, Link MP, Kavet R. Magnetic field exposure and long-term survival among children with leukaemia. Br J Cancer 94:161-164, 2006.

Foliart DE, Mezei G, Iriye R, Silva JM, Ebi KL, Kheifets L, Link MP, Kavet R, Pollock BH. Magnetic field exposure and prognostic factors in childhood leukemia. Bioelectromagnetics 28:69-71, 2007.

Forssén UM, Lonn S, Ahlbom, Savitz DA, and Feychting M. Occupational magnetic field exposure and the risk of acoustic neuroma. Am J Ind Med 49:112-8, 2006.

Framm J and Lautner S. Electrical signals and their physiological significance in plants. Plant Cell Environm 30: 249-257, 2007.

García AM, Sisternas A, Hoyos SP. Occupational exposure to extremely low frequency electric and magnetic fields and Alzheimer disease: a meta-analysis. Int J Epidemiol 37:329-40, 2008.

Gobba F, Bargellini A, Scaringi M, Bravo G, Borella P. Extremely low frequency-magnetic fields (ELF-EMF) occupational exposure and natural killer activity in peripheral blood lymphocytes. Sci Total Environ 407:1218-1223, 2009.

Greene RW. 60 Hz ultra-high voltage electric field effect on onion root mitotic index: a lack of impact. Environ Exp Bot 23:355-360, 1983.

Greenberg B, Bindokas VP, Gauger JR. Biological effects of a 765-kV transmission line: Exposures and thresholds in honeybee colonies. Bioelectromagnetics 2:315-328, 1981.

Greenland S, Sheppard AR, Kelsh MA, Kaune WT. A pooled analysis of magnetic fields, wire codes, and childhood leukemia. Epidemiology 11:624-634, 2000.

Groot C and Margolis L. (eds.). Pacific Salmon Life Histories. Vancourver: UBC Press, 1998.

Hardell L and Sage C. Biological effects from electromagnetic field exposure and public exposure standards. Biomedicine & Pharmacotherapy 62:104-109, 2008.

Harris AW, Basten A, Gebski V, Noonan D, Finnie J, Bath ML, Bangay MJ, Repacholi MH. A test of lymphoma induction by long-term exposure of E mu-Pim1 transgenic mice to 50 Hz magnetic fields. Radiat Res 149:300-307, 1998.

Health Council of the Netherlands (HCN). BioInitiative Report. U-5601/EvR/iv/673-L1 Publication nr 2008/17E. September 2008.

Health Council of the Netherlands (HCN). Health Council of the Netherlands; Reports 2008. The Hague: Health Council of the Netherlands. Publication No. A09/02, 2009.

Health Protection Agency (HPA). Power frequency electromagnetic fields, melatonin and the risk of breast cancer: report of an independent advisory group on non-ionising radiation. Doc HPA. Serious B: Radiation, Chemical and Environmental Hazards. RCE-1, 2006.

Her Majesty's Government (HMG) - Department of Health, Department for Communities and Local Government & Department of Energy and Climate Change. Government response to the Stakeholder Advisory Group on extremely low frequency electric and magnetic fields (ELF EMFs) (SAGE) recommendations. 16 October 2009. http://webarchive.nationalarchives.gov.uk/+/www.dh.gov.uk/en/Publichealth/Healthprotection/DH_4089500.

Hilson DW, Noggle JC, Burns ER. Effects of Electric Field on Plants Growing Under High Voltage Transmission Lines. Office of Natural Resources, Air Quality Branch. Tennessee Valley Authority. Chattanooga, Tennessee. 1983.

Hodges TK and Mitchell CA. Influence on High Intensity Electric Fields on Yield of Sweet Corn and Dent Corn-1982. A report for the American Electric Power Service Corporation. North Liberty, Indiana. 1984.

Hodges TK, Mitchell CA, Heydt G. Effect of Electric Fields from 765-kV Transmission Lines on Plant Growth. A report by Purdue University for Indiana and Michigan Electric Company, a Subsidiary of American Electric Power. New York, New York. 1975.

Huang H-H and Wang S-R. The effects of inverter magnetic fields on early seed germination of mung beans. Bioelectromagnetics 29: 649-657, 2008.

Hug K, Grize L, Seidler A, Kaatsch P, Schüz J. Parental occupational exposure to extremely low frequency magnetic fields and childhood cancer: A German case-control study. Am J Epidem 171:27-35, 2010.

Huss A, Spoerri A, Egger M, Röösli M, for the Swiss National Cohort Study. Residence near power lines and mortality from neurodegenerative diseases: longitudinal study of the Swiss population. Am J Epidemiol 169:167-175, 2009.

International Agency for Research on Cancer (IARC). Mechanisms of carcinogenesis in risk identification. No. 116. Lyon, France: IARC Press, 1992.

International Agency for Research on Cancer (IARC). IARC monographs on the evaluation of carcinogenic risks to humans. Volume 80: static and extremely low-frequency (ELF) electric and magnetic fields. Lyon, France: IARC Press, 2002.

International Commission on Non-Ionizing Radiation Protection (ICNIRP). Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Phys 74:494-522, 1998.

International Commission for Non-Ionizing Radiation Protection (ICNIRP). Review of the epidemiologic literature on EMF and health. Environ Health Perspect 109:S911-S933, 2001.

International Commission on Non-Ionizing Radiation Protection (ICNIRP). Exposure to Static and Low Frequency Electromagnetic Fields, Biological Effects and Health Consequences (0-100 kHz) – Review of the Scientific Evidence on Dosimetry, Biological Effects, Epidemiological Observations, and Health Consequences Concerning Exposure to Static and Low Frequency Electromagnetic Fields (0-100 kHz). Matthes R, McKinlay AF, Bernhardt JH, Vecchia P, Beyret B (eds.). International Commission on Non-Ionizing Radiation Protection, 2003.

International Commission on Non-ionizing Radiation Protection (ICNIRP). Draft Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz). Health Phys 96:504-514, 2009.

International Commission on Non-ionizing Radiation Protection (ICNIRP). Draft Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz). Health Phys 99:818-836, 2010.

International Committee on Electromagnetic Safety (ICES). IEEE Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Fields 0 to 3 kHz C95. 6-2002. Piscataway, NJ: IEEE, 2002.

Ivancsits S, Diem E, Pilger A, Rüdinger HW, Jahn O. Induction of DNA strand breaks by intermittent exposure to extremely-low-frequency electromagnetic fields in human diploid fibroblasts. Mutat Res 519:1-13, 2002a.

Ivancsits S, Pilger A, Diem E, Schaffer A, Rüdinger HW. Vanadate induces DNA strand breaks in cultured human fibroblasts at doses relevant to occupational exposure. Mutat Res 519:25-35, 2002b.

Ivancsits S, Diem E, Jahn O, Rüdiger HW. Age-related effects on induction of DNA strand breaks by intermittent exposure to electromagnetic fields. Mech Ageing Dev 124:847-850, 2003a.

Ivancsits S, Diem E, Jahn O, Rüdiger HW. Intermittent extremely low frequency electromagnetic fields cause DNA damage in a dose-dependent way. Int Arch Occup Environ Health 76:431-436, 2003b.

Johansen C and Olsen JH. Risk of cancer among Danish utility workers--a nationwide cohort study. Am J Epidemiol 147:548-55, 1998.

Johansen C, Raaschou-Nielsen O, Olsen JH, Schuez J. Risk for leukaemia and brain and breast cancer among Danish utility workers: A second follow-up. Occup Environ Med 64:782-4, 2007.

Johansson O. Disturbance of the immune system by electromagnetic fields – A potentially underlying cause for cellular damage and tissue repair reduction which could lead to disease and impairment. Pathophysiology 16:157-177, 2009.

Joosten S, Pammler K, Silny J. The influence of anatomical and physiological parameters on the interference voltage at the input of unipolar cardiac pacemakers in low frequency electric fields. Phys Med Biol 54:591-609, 2009.

Karipidis KK, Benke G, Sim MR, Yost M, and Giles G. Occupational exposure to low frequency magnetic fields and the risk of low grade and high grade glioma. Cancer Causes Control 18:305-13, 2007a.

Karipidis K, Benke G, Sim M, Fritschi L, Yost M, Armstrong B, Hughes AM, Grulich A, Vajdic CM, Kaldor J, and Kricker A. Occupational exposure to power frequency magnetic fields and risk of non-Hodgkin lymphoma. Occup Environ Med 64:25-9, 2007b.

Kavet R and Hooper HC. Residential magnetic fields and measures of neutral-to-earth voltage: Variability within and between residences. Health Physics 97:332-341, 2009.

Khaki AA, Zarrintan S, Khaki A, Zahedi A. The effects of electromagnetic field on the microstructure of seminal vesicles in rat: a light and transmission electron microscope study. Pakistan Journal of Biological Sciences 11:692-701, 2008.

Kheifets L and Oksuzyan S. Exposure assessment and other challenges in non-ionising radiation studies of childhood leukaemia**.** Exposure assessment and other challenges in non-ionizing radiation studies of childhood leukaemia. Radiat Prot Dosimetry 132: 139-147, 2008.

Kheifets L, Monroe J, Vergara X, Mezei G, Afifi A. Occupational electromagnetic fields and leukemia and brain cancer: An update to two meta-analyses. JOEM 50:677-88, 2008.

Kheifets L, Bowman JD, Checkoway H, Feychting M, Harrington JM, Kavet R, Marsh G, Mezei G, Renew DC and van Wijngaarden E. Future needs of occupational epidemiology of extremely low frequency electric and magnetic fields: review and recommendations. Occupational and Environmental Medicine 66:72-80, 2009.

Kheifets L, Ahlbom A, Crespi CM, Draper G, Hagihara J, Lowenthal RM, Mezei G, Oksuzyan S, Schüz J, Swanson J, Tittarelli A, Vincenti M, Wunsch Filho V. Pooled analysis of recent studies on magnetic fields and childhood leukaemia. British Journal of Cancer 103:1128-1135, 2010.

Kim Y-W, Kim H-S, Lee J-S, Kim Y-J, Lee S-K, Seo J-N, Jung K-C, Kim N, Gimm Y-M. Effects of 60 Hz 14 μT magnetic field on the apoptosis of testicular germ cell in mice. Bioelectromagnetics 30: 66-72, 2009.

Kirschvink, JL; Diaz Ricci, J; Nesson, MH; Kirschvink, SJ Magnetite-based magnetoreceptors in animals: structural, behavioral, and biophysical studies. Palo Alto: Electric Power Research Institute (EPRI), TR-102008, September 1993.

Kirschvink JL, Padmanabha S, Boyce KC, Ogelsby J. Measurement of the threshold sensitivity of honeybees to weak, extremely low-frequency magnetic fields. Journal of Experimental Biology 200:1363-1368, 1997.

Krizaj D and Valencic V. The effects of ELF magnetic fields and temperature on differential plant growth. Journal of Bioelectricity 8:159-165, 1989.

Kroll ME, Swanson J, Vincent TJ, Draper GJ. Childhood cancer and magnetic fields from high-voltage power lines in England and Wales: a case-control study. British Journal of Cancer 103:1122-1127, 2010.

Lai H and Singh NP. Magnetic-field-induced DNA strand breaks in brain cells of the rat. Environ Health Perspect 112:687-694, 2004.

Lee JM and Clark CF. Ecological Effects of EHV and UHV Transmission Lines Current Issues. In: CIRGE Symposium on Transmission Lines and the Environment. June 23-25. Stockholm, Sweden. 223-307, 1981.

Lee GM, Neutra RR, Hristova L, Yost M, Hiatt RA. A nested case-control study of residential and personal magnetic field measures and miscarriages. Epidemiology 13:21-31, 2002.

Li DK, Odouli R, Wi S, Janevic T, Golditch I, Bracken TD, Senior R, Rankin R, Iriye R. A population-based prospective cohort study of personal exposure to magnetic fields during pregnancy and the risk of miscarriage. Epidemiology 13:9-20, 2002.

Li P, McLaughlin J, Infante-Rivard C. Maternal occupational exposure to extremely low frequency magnetic fields and the risk of brain cancer in the offspring. Cancer Causes Control 20:945-955, 2009.

Linet MS, Hatch EH, Kleinerman A, Robinson LL, Kaune WT, Friedman DR, Severson RK, Haines CM, Hartsock CT, Niwa S, Wachholder S, and Tarone RE. Residential exposure to magnetic fields and acute lymphoblastic leukemia in children. N Engl J Med 337:1-7, 1997.

Löscher W, Mevissen M, Lehmacher W, Stamm A. Tumor promotion in a breast cancer model by exposure to a weak alternating magnetic field. Cancer Lett 71:75-81, 1993.

Löscher W, Wahnschaffe U, Mevissen M, Lerchl A, Stamm A. Effects of weak alternating magnetic fields on nocturnal melatonin production and mammary carcinogenesis in rats. Oncology 51:288-295, 1994.

Löscher W, Mevissen M, Haussler B. Seasonal influence on 7,12-dimethylbenz[a]anthracene-induced mammary carcinogenesis in Sprague-Dawley rats under controlled laboratory conditions. Pharmacol Toxicol 81:265-270, 1997.

Löscher W and Mevissen M. Linear relationship between flux density and tumor co-promoting effect of prolonged magnetic field exposure in a breast cancer model. Cancer Lett 96:175-180, 1995.

Lowenthal RM, Tuck DM, Bray IC. Residential exposure to electric power transmission lines and risk of lymphoproliferative and myeloproliferative disorders: a case-control study. Internal Med J 37:614-9, 2007.

Malagoli C, Fabbi S, Teggi S, Calzari M, Poli M, Ballotti E, Notari B, Bruni M, Plazaai G, Paolucci P, Vinceti M. Risk of hematological malignancies associated with magnetic fields exposure from power lines: A case control study in two municipalities of northern Italy. Environ Health 9:16, 2010.

Mandeville R, Franco E, Sidrac-Ghali S, Paris-Nadon L, Rocheleau N, Mercier G, Desy M, Gaboury L. Evaluation of the potential carcinogenicity of 60 Hz linear sinusoidal continuous-wave magnetic fields in Fisher F344 rats. FASEB Journal 11:1127-1136, 1997.

Mann, S.; Sparks, N.H.C.; Walker, M.M.; Kirschvink, J.L. Ultrastructure, Morphology and Organization of Biogenic Magnetite from Sockeye Salmon, *Oncorhynchus nerka*: Implications for Magnetoreception. Journal of Experimental Biology 140:35-49, 1988.

Maslanyj M, Simpson J, Roman E, Schüz J. Power frequency magnetic fields and risk of childhood leukaemia: Misclassification of exposure from the use of the distance from power line' exposure surrogate. Bioelectromagnetics 30:183-188, 2009

McBride ML, Gallagher RP, Thériault G, Armstrong BG, Tamaro S, Spinelli JJ, Deadman JE, Fincham S, Robson D, Choi W. Power-frequency electric and magnetic fields and risk of childhood leukemia in Canada. Am J Epidemiol 149:831-42, 1999.

McCormick DL, Boorman GA, Findlay JC, Hailey JR, Johnson TR, Gauger JR, Pletcher JM, Sills RC, Haseman JK. Chronic toxicity/oncogenicity evaluation of 60 Hz (power frequency) magnetic fields in B6C3F1 mice. Toxicol Pathol 27:279-85, 1999.

McElroy JA, Egan KM, Titus-Ernstoff L, Anderson HA, Trentham-Dietz A, Hampton JM, Newcomb PA. Occupational exposure to electromagnetic field and breast cancer risk in a large, population-based, case-control study in the United States. J Occup Environ Med 49:266-74, 2007.

McKee GW, Knievel DP, Poznaniak DT, Bankoske JW. Effects of 60 Hz high intensity electric fields on living plants. IEEE Transactions on Power Apparatus Systems 97:1177-1181, 1978.

McNally RJQ and Parker L. Environmental factors and childhood acute leukemias and lymphomas. Leukemia & Lymphoma 47:583-98, 2006.

Mejia-Arangure JM, Fajardo-Gutierrez A, Perez-Saldivar ML, Gorodezky C, Martinez-Avalos A, Romero-Guzman L, Campo-Martinez MA, Flores-Lujano J, Salamanca-Gomez F, Velasquez-Perez L. Magnetic fields and acute leukemia in children with Down syndrome. Epidemiology 18:158-61, 2007.

Mevissen M, Stamm A, Buntenkotter S, Zwingelberg R, Wahnschaffe U, Löscher W. Effects of magnetic fields on mammary tumor development induced by 7,12-dimethylbenz(a)anthracene in rats. Bioelectromagnetics 14:131-143, 1993a.

Mevissen M, Wahnschaffe U, Löscher W, Stamm A, Lerchl A. Effects of AC magnetic field on DMBA-induced mammary carcinogenesis in Sprague-Dawley rats. In: Electricity and Magnetism in Biology and Medicine. Blank M (ed). San Francisco Press, pp. 413-415, 1993b.

Mevissen M, Lerchl A, Löscher W. Study on pineal function and DMBA-induced breast cancer formation in rats during exposure to a 100-mG, 50 Hz magnetic field. J Toxicol Environ Health 48:169-185, 1996a

Mevissen M, Lerchl A, Szamel M, and Löscher W. Exposure of DMBA-treated female rats in a 50 Hz, 50-μT magneticfield: effects on mammary-tumor growth, melatonin levels, and T-lymphocyte activation. Carcinogenesis 17:903-910, 1996b.

Mevissen M, Haussler M, Lerchl A, Löscher W. Acceleration of mammary tumorigenesis by exposure of 7,12-dimethylbenz[a]anthracene-treated female rats in a 50 Hz, 100-microT magnetic field: replication study. J Toxicol Environ Health A 53:401-418, 1998.

Mezei G, Bracken TD, Senior R, Kavet R. Analyses of magnetic-field peak-exposure summary measures. J Expo Sci Environ Epidemiol 16:477-85, 2006.

Mezei G and Kheifets L. Selection bias and its implications for case-control studies: a case study of magnetic field exposure and childhood leukaemia. Int J Epidemiol 35:397-406, 2006.

Mezei G, Gadallah M, Kheifets L. Residential magnetic field exposure and childhood brain cancer: a meta-analysis. Epidemiology 29:424-30, 2008a.

Mezei G, Spinelli JJ, Wong P, Borugian M, McBride ML. Assessment of selection bias in the Canadian case-control study of residential magnetic field exposure and childhood leukemia. Am J Epidemiol 167:1504-10, 2008b.

Mihai R, Cogalniceanu G, Brezeanu, A. Control of *nicotiana tabacum callus* growth by alternating and pulsed electric field. Electro- and Magnetobiology 13:195-201, 1994.

Miller MW, Carstensen EL, Kaufman GE, Robertson D. 60-Hz electric field parameters associated with the perturbation of a eukaryotic system. In: Biological effects of extremely low frequency electromagnetic fields. Proceedings of the Eighteenth Annual Hanford Life Sciences Symposium at Richland, Washington, October 16-18, 1978.

Mostafa RM, Moustafa YM, Ali FM, Shafik A. Sex hormone status in male rats after exposure to 50 Hz, 5 mT magnetic field. Archives of Andrology 52:363-369, 2006.

National Academy of Sciences (NAS), National Research Council. Possible Effects of Electromagnetic Fields on Biologic Systems. Washington, DC: National Academy of Sciences Press, 1997.

National Institute of Environmental Health Sciences (NIEHS). Assessment of health effects from exposure to power-line frequency electric and magnetic fields: working group report. NIH Publication No. 98-3981. Research Triangle Park, NC: National Institute of Environmental Health Sciences of the U.S. National Institutes of Health, 1998.

National Institute of Environmental Health (NIEHS). Health effects from exposure to power line frequency electric and magnetic fields. NIH Publication No. 99-4493. Research Triangle Park, NC: National Institute of Environmental Health Sciences of the U.S. National Institutes of Health, 1999.

National Institute of Environmental Health (NIEHS). EMF Electric and Magnetic Fields Associated with the use of Electric Power: Questions and Answers. Research Triangle Park, NC: National Institute of Environmental Health Sciences of the U.S. National Institutes of Health, 2002.

National Radiological Protection Board (NRPB). Electromagnetic fields and the risk of cancer. Report of an Advisory Group on Non-ionising Radiation. National Radiological Protection Board 3(1):1-138, 1992.

National Radiological Protection Board (NRPB). Electromagnetic fields and the risk of cancer. Supplementary report by the Advisory Group on Non-ionising Radiation. National Radiological Protection Board 4(5):65-69, 1993.

National Radiological Protection Board (NRPB). Electromagnetic fields and the risk of cancer. Supplementary report by the Advisory Group on Non-ionising Radiation. National Radiological Protection Board 5(2):77-81, 1994a.

National Radiological Protection Board (NRPB). Health effects related to the use of visual display units. Report of an Advisory Group on Non-ionising Radiation. National Radiological Protection Board 5(2):1-75, 1994b.

National Radiological Protection Board (NRPB). ELF Electromagnetic Fields and the Risk of Cancer: Report of an Advisory Group on Non-ionising Radiation. National Radiological Protection Board. Volume 12, No 1, 2001a.

National Radiological Protection Board (NRPB). ELF Electromagnetic fields and neurodegenerative disease. National Radiological Protection Board. Volume 12, No 4, 2001b.

National Radiological Protection Board (NRPB). Review of the scientific evidence for limiting exposure to electromagnetic fields (0-300 GHz). National Radiological Protection Board (NRPB). Volume 15, No 3, 2004.

National Research Council; Commission on Life Sciences; Board on Radiation Effects Research; Committee on the Possible Effects of Electromagnetic Fields on Biologic Systems. Possible Health Effects of Exposure to Residential Electric and Magnetic Fields. Washington, DC: National Academy Press. 1997a.

National Research Council. An Evaluation of the U.S. Navy's Extremely Low Frequency Communications System Ecological Monitoring Program. National Academy Press, Washington, D.C. 162 pp. 1997b.

National Toxicology Program (NTP). NTP technical report on the toxicology and carcinogenesis studies of 60 Hz magnetic fields in F344/N rats and B6C3F1 mice. Washington DC, National Toxicology Program. NTP TR 488, NIH Publication No. 99-3979. 1999.

Negishi T, Imai S, Shibuya K, Nishimura I, Shigemitsu T. Lack of promotion effects of 50 Hz magnetic fields on 7,12-dimethylbenz(a)anthracene-induced malignant lymphoma/lymphatic leukemia in mice. Bioelectromagnetics 29:29-38, 2008.

Neutra RR and Li D. Letter to the Editor – Magnetic fields and miscarriage: A commentary on Mezei et al., JESEE 2006. JESEE 18:537-540, 2008.

New York Public Service Commission (NYPSC). Opinion No. 78-13. Opinion and Order Determining Health and Safety Issues, Imposing Operating Conditions, and Authorizing, in Case 26529, Operation Pursuant to Those Conditions. Issued June 19, 1978.

New York Public Service Commission (NYPSC). Statement of Interim Policy on Magnetic Fields of Major Transmission Facilities. Cases 26529 and 26559 Proceeding on Motion of the Commission. Issued and Effective: September 11, 1990.

Okudan B, Keskin AU, Aydin MA, Cesur G, Comlekci S, Suslu H. DEXA analysis on the bones of rats exposed in utero and neonatally to static and 50 Hz electric fields. Bioelectromagnetics 27:589-92, 2006.

Parsch LD and Norman MD. Impact of power lines on crop yields in eastern Arkansas. Arkansas Farm Research (September-October):4, 1986.

Pearce MS, Hammal DM, Tevfik Dorak M, McNally RJQ, Parker L. Paternal occupational exposure to electro-magnetic fields as a risk factor for cancer in children and young adults: A case-control study from the north of England. Pediatr Blood Cancer 49:280-286, 2007.

Poulletier de Gannes F, Ruffie G, Taxile M, Ladeveze E, Hurtier A, Haro E, Duleu S, Charlet de Sauvage R, Billaudel B, Geffard M, Veyret B, Lagroye I. Amyotrophic lateral sclerosis (ALS) and extremely-low frequency (ELF) magnetic fields: a study in the SOD-1 transgenic mouse model. Amyotroph Lateral Sclerosis, 2008 (e-pub ahead of print).

Quinn TP, Merrill RT, Brannon EL. Magnetic field detection in Sockeye salmon. Journal of Experimental Zoology 217:137-142, 1981.

Quinn TP and Brannon EL. The Use of Celestial and Magnetic Cues by Orienting Sockeye Salmon Smolts. Journal of Comparative Physiology 147:547-552, 1982.

Rajaei F, Borhani N, Sabbagh-Ziarani F, Mashayekhi F. Effects of extremely low-frequency electromagnetic field on fertility and heights of epithelial cells in pre-implantation stage endometrium and fallopian tube in mice. Journal of Chinese Integrative Medicine 8:56-60, 2010.

Ray RM, Gao DL, Li W, Wernli KJ, Astrakianakis G, Seixas NS, Camp JE, Fitzgibbons ED, Feng Z, Thomas DB, and Checkoway H. Occupational exposures and breast cancer among women textile workers in Shanghai. Epidemiology 18:383-92, 2007.

Reed DD, Jones EA, Mroz GD, Liechty HO, Cattelino PJ, Jurgensen MF. Effects of 76 Hz electromagnetic fields on forest ecosystems in northern Michigan: tree growth. Int J Biometeorol 37:229-234, 1993.

Reilly JP. An analysis of differences in the low-frequency electric and magnetic field exposure standards of ICES AND ICNIRP. Health Physics 89:71-80, 2005.

Rodriguez M, Petitclerc D, Burchard JF, Nguyen DH, Block E. Blood melatonin and prolactin concentrations in dairy cows exposed to 60 Hz electric and magnetic fields during 8 h photoperiods. Bioelectromagnetics 25:508-515, 2004.

Rodriguez M, Petitclerc D, Burchard JF, Nguyen DH, Block E, Downey BR. Responses of the estrous cycle in dairy cows exposed to electric and magnetic fields (60 Hz) during 8-h photoperiods. Anim Reprod Sci 77:11-20, 2003.

Rodriguez M, Petitclerc D, Nguyen DH, Block E, Burchard JF. Effect of electric and magnetic fields (60 Hz) on production, and levels of growth hormone and insulin-like growth factor 1, in lactating, pregnant cows subjected to short days. J Dairy Sci 85:2843-2849, 2002.

Rogers LE, Warren JL, Gano KA, Hinds NR, Fitzner RE, Gilbert RO. Environmental Studies of a 1100-kV Prototype Transmission Line: An Interim Report. Prepared by Batelle Pacific Northwest Laboratories for Bonneville Power Administration. Portland, Oregon, 1980.

Rogers LE, Warren JL, Hinds NR, Gano KA, Fitzner RE, Piepel GF. Environmental Studies of a 1100-kV Prototype Transmission Line: Annual report for the 1980 Study Period. Battelle Pacific Northwest Laboratories. Portland, Oregon. 1981.

Rogers LE, Warren NR, Hinds KA, Gano RE, Fitzner RE, Peipel GF. Environmental Studies of a 1100-kV Prototype Transmission Line: An Annual Report for the 1981 Study Period. Prepared by Battelle Pacific Northwest Laboratories for Bonneville Power Administration. Portland, Oregon. 1982.

Röösli M, Lörtscher M, Egger M, Pfluger D, Schreirer N, Emanuel L, Locher P, Spoerri A, Minder C. Leukaemia, brain tumours and exposure to extremely low frequency magnetic fields: cohort study of Swiss railway employees. Occup Environ Med 64:553-9, 2007a.

Röösli M, Lörtscher M, Egger M, Pfluger D, Schreirer N, Lörtscher E, Locher P, Spoerri A, Minder C. Mortality from neurodegenerative disease and exposure to extremely low-frequency magnetic fields: 31 years of observations on Swiss railway employees. Neuroepidemiol 28:197-206, 2007b.

Roushanger L and Soleimani Rad J. Ultrastructural alterations and occurrence of apoptosis in developing follicles exposed to low frequency electromagnetic field in rat ovary. Pakistan Journal of Biological Sciences 10:4413-4419, 2007.

Ruzic R, Jerman I, Jeglic A, Fefer D. Electromagnetic stimulation of buds of *Castanea sativa, mill*. In tissue culture. Electro- and Magnetobiology 11:145-153, 1992.

Saito T, Nitta H, Kubo O, Yamamoto S, Yamaguchi N, Akiba S, Honda Y, Hagihara J, Isaka K, Ojima T, Nakamura Y, Mizoue T, Ito S, Eboshida A, Yamazaki S, Sokejima S, Kurokawa Y, Kabuto M. Power-frequency magnetic fields and childhood brain tumors: A case-control study in Japan. J Epidemiol 20:54-61, 2010.

Santibáñez M, Bolumar F, García AM. Occupational risk factors in Alzheimer's disease: a review assessing the quality of published epidemiological studies. Occup Environ Med 64:723-732, 2007.

Savitz DA. Magnetic fields and miscarriage. Epidemiology 13:1-4, 2002.

Savitz DA. The etiology of epidemiologic perseveration: when enough is enough. Epidemiology 21:281-283, 2010.

Savitz DA, Checkoway H, Loomis DP. Magnetic field exposure and neurodegenerative disease mortality among electric utility workers. Epidemiology 9:398-404, 1998.

Savitz DA, Herring AH, Mezei G, Evenson KR, Terry JW Jr, Kavet R. Physical activity and magnetic field exposure in pregnancy. Epidemiology 17:222-225, 2006.

Scarfi MR, Sannino A, Perrotta A, Sarti M, Mesirca P, Bersani F. Evaluation of genotoxic effects in human fibroblasts after intermittent exposure to 50 Hz electromagnetic fields: a confirmatory study. Radiat Res 164:270-6, 2005.

Scholten A and Silny, J. The interference threshold of cardiac pacemakers in electric 50 Hz fields. J Med Eng Technol 25:1-11, 2001.

Schüz J and Ahlbom A. Exposure to electromagnetic fields and the risk of childhood leukaemia: A review. Radiat Prot Dosimetry 132:202-211, 2008.

Schüz J, Svendsen AL, Linet MS, McBride ML, Roman E, Feychting M, Kheifets L, Lightfoot T, Mezei G, Simpson J, Ahlbom A. Nighttime exposure to electromagnetic fields and childhood leukemia: an extended pooled analysis. Am J Epidemiol 166:263-269, 2007.

Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR). Possible Effects of Electromagnetic Fields (EMF) on Human Health. European Commission. Directorate C – Public Health and Risk Assessment, 2007.

Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) for the Directorate-General for Health & Consumers of the European Commission. Health Effects of Exposure to EMF. January 2009.

Scientific Committee on Toxicity, Ecotoxicity and the Environment (CSTEE). Possible Effects of Electromagnetic Fields (EMF), Radio Frequency Fields (RF) and Microwave Radiation on Human Health. 2001.

Scientific Steering Committee (SSC). Opinion on possible health effects from exposure to electromagnetic fields (0 Hz- 300 GHz) - Report and opinion adopted at the meeting of the Scientific Steering Committee of 25-26 June 1998.

Schmiedel S and Blettner M. The association between extremely-low frequency fields and childhood leukaemia in epidemiology: enough is enough? Br J Cancer 103:931-932, 2010.

Scholten A and Silny J. The interference threshold of cardiac pacemakers in electric 50 Hz fields, Journal of Medical Engineering and Technology 25: 1-11, 2001.

Seidler A, Geller P, Nienhaus A, Bernhardt T, Ruppe I, Eggert S, Hietanen M, Kauppinen T, and Frolich L. Occupational exposure to low frequency magnetic fields and dementia: a case-control study. Occup Environ Med 64:108-14, 2007.

Seyhan N and Canseven AG. In vivo effects of ELF MFs on collagen synthesis, free radical processes, natural antioxidant system, respiratory burst system, immune system activities, and electrolytes in the skin, plasma, spleen, lung, kidney, and brain tissues. Electromagnetic Biology and Medicine 25:291-305, 2006.

Smith SD, McLeod BR, Liboff AR. Effects of CR-tuned 60 Hz magnetic fields on sprouting and early growth of Raphanus sativus. Bioelectrochem Bioenerg 32:67-76, 1993.

Sobel E, Dunn M, Davanipour Z, Qian Z and Chui HC. Elevated risk of Alzheimer's disease among workers with likely electromagnetic fields exposure. Neurology 47:1477-81, 1996.

Sommer AM and Lerchl A. The risk of lymphoma in AKR/J mice does not rise with chronic exposure to 50 Hz magnetic fields (1 microT and 100 microT). Radiat Res 162:194-200, 2004.

Sommer AM and Lerchl A. 50 Hz magnetic fields of 1 mT do not promote lymphoma development in AKR/J mice. Radiat Res 165:343-349, 2006.

Sorahan T and Kheifets L. 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. Occup Environ Med 64:820–826, 2007.

Svendsen AL, Weihkopf T, Kaatsch P, Schuz J. Exposure to magnetic fields and survival after diagnosis of childhood leukemia: a German cohort study. Cancer Epidemiol Biomarkers Prev 16:1167-71, 2007.

Swedish Radiation Protection Authority (SSI). Fourth annual report from SSI's Independent Expert Group on Electromagnetic Fields, 2006: Recent Research on EMF and Health Risks. SSI Rapport 2007:04.

Swedish Radiation Protection Authority (SSI). Fifth annual report from SSI's Independent Expert Group on Electromagnetic Fields, 2007: Recent Research on EMF and Health Risks. SSI Rapport 2008:12.

Toivonen L, Metso R, Valjus J, Hongisto M. The influence of 50-Hz electric and magnetic fields on cardiac pacemakers. Imatran Voima Oy Research Reports; Helsinki, 1991.

Ueda H, Kaeriyama M, Mukasa K, Urano A, Kudo H, Shoji T, Tokumitsu Y, Yamauchi K, Kurihara K. Lacustrine Sockeye Salmon Return Straight to their Natal Area from Open Water Using Both Visual and Olfactory Cues. Chemical Senses 23:207-212, 1998.

United Kingdom Childhood Cancer Study Investigators. Childhood cancer and residential proximity to power lines. Br J Cancer 83:1573-1580, 2000.

US Environmental Protection Agency (USEPA). Guidelines for carcinogen risk assessment and supplemental guidance for assessing susceptibility from early-life exposure to carcinogens. EPA/630/P-03/001F, 2005.

US Department of Health and Human Services (HHS), Health Resources and Services Administration, Maternal and Child Health Bureau. Child Health USA 2004. Rockville, MD: US Department of Health and Human Services, 2004.

Walker MM, Quinn TP, Kirschvink JL, Groot C. Production of single-domain magnetite throughout life by sockeye salmon, *oncorhynchus nerka*. J Exp Biol 1988; 140:51-63.

Warren NR, Hinds KA, Gano RE, Fitzner RE, Piepel GF. Environmental Studies of a 1100-kV Prototype Transmission Line: an Annual Report for the 1980 Study Period. Prepared by Battelle Pacific Northwest Laboratories for Bonneville Power Administration. Portland, Oregon. 1981.

Wiltschko W, Wiltschko, R. Orientation by the earth's magnetic field in migrating birds and homing pigeons. pp. 31-43. In: Effects of Atmospheric and Geophysical Variables in Biology and Medicine: Biometeorology. H. Lieth (ed). The Hague: SPB Academic Publishing, 1991.

Wong O, Harris F, Wang Y, Fu H. 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. J Occup Environ Med 52:39-53, 2010.

World Health Organization (WHO). Framework for Developing Health-Based Standards. Geneva, Switzerland: World Health Organization, 2006.

World Health Organization (WHO). Environmental Health Criteria 238: Extremely Low Frequency (ELF) Fields. WHO, Geneva, Switzerland, ISBN 978-92-4-157238-5, 2007a.

World Health Organization (WHO). Fact sheet No. 322: Electromagnetic Fields and Public Health – Exposure to Extremely Low Frequency Fields. World Health Organization, June 2007b.

Yang Y, Jin X, Yan C, Tian Y, Tang J, Shen X. Case-only of interactions between DNA repair genes (hMLH1, APEX1, MGMT, XRCC1 and XPD) and low-frequency electromagnetic fields in childhood acute leukemia. Leukemia & Lymphoma 49:2344-2350, 2008

Yano AM, Ogura M, Sato A, Sakaki Y, Shimizu Y, Baba N, Nagasawa K. Effect of modified magnetic field on the ocean migration of maturing chum salmon, *Oncorhynchus keta*. Marine Biology 129:523-530, 1997.

Yasui M, Kikuchi T, Ogawa M, Otaka Y, Tsuchitani M, Iwata H. Carcinogenicity test of 50 Hz sinusoidal magnetic fields in rats. Bioelectromagnetics 18:531-540, 1997.

Yao K, Yu Y, Wang KJ, Ye J, Lu DQ, Jiang H. Absence of effect of power-frequency magnetic fields exposure on mouse embryonic lens development. Bioelectromagnetics 28:628-635, 2007.

Zapotosky JE, Gauger JR, Haradem DP. ELF Communications System Ecological Monitoring Program: Final Summary Report. Washington, DC: Space and Naval Warfare Systems Command, Report No. D06214-6. Prepared by IIT Research Institute, Chicago, IL. February. Available through NTIS. 1996

Appendix 1

World Health Organization
International EMF Project
Summary of Conclusions

Overview

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

The Monograph used standard scientific procedures, as outlined in the Preamble, to conduct its weight-of-evidence review.[1] The Task Group responsible for the report's overall conclusions consisted of 21 scientists from around the world with expertise in a wide range of disciplines. The Task Group relied on the conclusions of previous weight-of-evidence reviews, where possible, and (with regard to cancer) mainly focused on evaluating studies published after the IARC review in 2002. Specific terms were used by the Task Group to describe the strength of the evidence in support of causality. *Limited evidence* describes a body of research where the findings are inconsistent or there are outstanding questions about study design or other methodological issues that preclude making strong conclusions. *Inadequate evidence* describes a body of research where it is unclear whether the data is supportive or unsupportive of causation because there is a lack of data or there are major quantitative or qualitative issues.

The following sections describe the conclusions of the WHO by health outcome (cancer, reproductive effects, and neurodegenerative diseases). The conclusions and perspectives of

[1] The term "weight-of-evidence review" is used in this report to denote a systematic review process by a multidisciplinary, scientific panel involving experimental and epidemiologic research to arrive at conclusions about possible health risks. The WHO Monograph on EMF does not specifically describe their report as a weight-of-evidence review. Rather, they describe conducting a health risk assessment. Although the two terms are similar, a health risk assessment differs from a weight-of-evidence review in that it also incorporates an exposure assessment and an exposure-response assessment.

weight-of-evidence reviews conducted by other scientific organizations are discussed, where appropriate, to highlight consistencies and inconsistencies in conclusions.

Conclusions

Cancer

The overwhelming majority of health research related to EMF has focused on the possibility of a relationship with cancer, including leukemia, lymphoma, breast cancer, and brain cancer. The vast majority of epidemiologic studies in this field enrolled persons with a specific cancer type (*cases*); selected a group of individuals similar to the cancer cases (*controls*); estimated past magnetic or electric field exposures, or both; and compared these exposures between the cases and controls to test for statistical differences. Some of these studies looked for statistical associations of these diseases with magnetic fields produced by nearby power lines (estimated through calculations or distance) or appliances, while other studies actually measured magnetic field levels in homes or estimated personal magnetic field exposures from all sources. In studies of adult cancers, occupational magnetic field exposures were estimated in some studies, as well. *In vivo* studies in this field exposed animals to high levels of magnetic fields (up to 50,000 milligauss [mG]) over the course of their entire lifetime to observe whether exposed animals had higher rates of cancer than unexposed animals. Some of these studies exposed animals to magnetic fields in tandem with a known carcinogen to test whether magnetic field exposure promoted carcinogenesis. Since there is relatively low energy associated with extremely low-frequency (ELF) EMF, researchers believe it is highly unlikely that electric or magnetic fields can directly damage DNA. Therefore, *in vitro* studies in this field have largely focused on investigating whether ELF EMF could promote damage from other known carcinogens or cause cancer through a pathway other than DNA damage (e.g., hormonal or immune effects or alterations in signal transduction).

The International Agency for Research on Cancer (IARC) is the division of the WHO with responsibility to coordinate and conduct research on the causes of human cancer and the mechanisms of carcinogenesis and to develop scientific strategies for cancer control. The IARC convened a scientific panel in 2001 to conduct an extensive review and arrive at a conclusion about the possible carcinogenicity of EMF (IARC, 2002). The IARC has a standard method for classifying exposures based on the strength of the scientific research in support of carcinogenicity.

Categories include (from highest to lowest risk): carcinogenic to humans, probably carcinogenic to humans, possibly carcinogenic to humans, unclassifiable, and probably not carcinogenic to humans. As a result of two pooled analyses reporting an association between high, average magnetic field exposure and childhood leukemia, the epidemiology data was classified as providing "limited evidence of carcinogenicity"[2] in relation to childhood leukemia. With regard to all other cancer types, the epidemiology evidence was classified as inadequate. The IARC panel also reported that there was "inadequate evidence of carcinogenicity" in studies of experimental animals. Overall, magnetic fields were evaluated as "possibly carcinogenic to humans." The IARC usage of "*possible*" denotes an exposure in which epidemiologic evidence points to a statistical association, but other explanations cannot be ruled out as the cause of that statistical association (e.g., bias and confounding)[3] and experimental evidence does not support a cause-and-effect relationship. Considering recently published epidemiology, *in vivo,* and *in vitro* research, the WHO concluded that the classification of "possible carcinogen" remains accurate (WHO, 2007).

Childhood Leukemia

The issue that has received the most attention is childhood leukemia. Research in this area was prompted by an epidemiology study of children in the United States that reported a statistical association between childhood leukemia and a higher predicted magnetic field level in the home based on characteristics of nearby distribution and transmission lines (Wertheimer and Leeper, 1979). Subsequently, some epidemiologic studies reported that children with leukemia were more likely to live closer to power lines or have higher estimates of magnetic field exposure (compared to children without leukemia), while other epidemiologic studies did not report this statistical association. Of note, the largest epidemiology studies of childhood leukemia that actually measured personal magnetic field exposure (as opposed to estimating exposure through

[2] Each type of evidence is categorized based on the strength of the evidence in support of carcinogenicity. The categories include: sufficient evidence of carcinogenicity, limited evidence of carcinogenicity, inadequate evidence of carcinogenicity, and evidence suggesting lack of carcinogenicity. If a positive association between an exposure and cancer is found (although factors such as chance, bias and confounding cannot be ruled out with reasonable confidence), the epidemiologic evidence is rated as "limited evidence of carcinogenicity." If chance, bias and confounding can be ruled out with reasonable confidence, then the evidence is classified as "sufficient evidence of carcinogenicity." The *in vivo* studies are ranked using a similar system, and the totality of the evidence is then considered to reach a conclusion about a particular exposure's carcinogenicity.

[3] Bias refers to any systematic error in the design, implementation or analysis of a study that results in a mistaken estimate of an exposure's effect on the risk of disease. A confounder is something that is related to both the disease under study and the exposure of interest such that we cannot be sure what causes the observed association - the confounder or the exposure of interest.

calculations or distance) did not report evidence to support a causal relationship, nor did they report a dose-response relationship with exposure to higher magnetic field levels (Linet et al., 1997; McBride et al., 1999; UKCCS, 1999).

In 2000, researchers combined the data from previously published epidemiology studies of magnetic fields and childhood leukemia that met specified criteria (Ahlbom et al., 2000; Greenland et al., 2000). The researchers pooled the data on the individuals from each of the studies, creating a study with a much larger number of subjects and, as a result, greater statistical power to detect an effect (should one exist) than any single study. In both pooled analyses, a weak association was reported between childhood leukemia and estimates of average magnetic field exposures greater than 3-4 mG. The authors were appropriately cautious in the interpretation of their analyses, and noted the uncertainty related to pooling estimates of exposure obtained by different methods from studies of diverse design, as did other researchers (e.g., Elwood, 2006). Because of the inherent uncertainty associated with observational epidemiologic studies, the results of these pooled analyses were not considered to provide strong epidemiologic support for a causal relationship. Furthermore, *in vivo* studies have not found that magnetic fields induce or promote cancer in animals exposed under highly controlled conditions for their entire lifespan, nor have *in vitro* studies found a cellular mechanism by which magnetic fields could induce carcinogenesis. As discussed above, these findings resulted in the classification of magnetic fields as a possible carcinogen (IARC, 2002).

The WHO evaluated two more recently published studies related to childhood leukemia and magnetic fields (Draper et al, 2005; Kabuto et al., 2006). Draper et al. conducted a case-control study of childhood cancer, which included 9,700 children with leukemia (i.e., cases) and an equal number of children that did not have leukemia (i.e., controls). The study compared the distance of birth address to high-voltage transmission lines among cases and controls and reported a weak association between childhood leukemia and birth addresses within 600 feet of high-voltage transmission lines. Kabuto et al. conducted a smaller case-control study in Japan that measured the average weekly magnetic field in the bedrooms of 312 children with leukemia and 603 children without leukemia. The investigators reported that children with leukemia were more likely to have average magnetic field levels >4 mG compared to children without leukemia.

The WHO did not assign a high weight or significance to these studies in their overall evaluation, stating that the low participation rate in Kabuto et al. and the use of distance as a proxy for magnetic field exposure in Draper et al. were important limitations. Less weight should be placed on these studies relative to studies that used good exposure assessment techniques and had high participation rates. The WHO described the results of these two studies as consistent with the classification of limited epidemiologic evidence in support of carcinogenicity and, together with the largely negative *in vivo* and *in vitro* research, consistent with the classification of magnetic fields as a possible carcinogen.

The WHO concluded that several factors might be fully, or partially, responsible for the consistent association observed between high, average magnetic fields and childhood leukemia, including misclassification of magnetic field exposure due to poor exposure assessment methods, confounding from unknown risk factors, and selection bias.[4] The WHO concluded that reconciling the epidemiologic data on childhood leukemia and the negative (i.e., no hazard) experimental findings through innovative research is currently the highest priority in the field of ELF EMF research. Given that few children are expected to have average magnetic field exposures greater than 3-4 mG, however, the WHO stated that the public health impact of magnetic fields on childhood leukemia would be low if the association were causal.

Breast Cancer

Research on breast cancer has examined the possible effects of ELF EMF from three sources: workplace exposures, residential exposure from power lines, and electric blankets. Some of the early epidemiology studies in this field reported a weak association between breast cancer and higher magnetic field exposures, while others did not; however, the conclusions that could be drawn from this initial body of research were limited because of study quality issues (e.g., poor exposure assessment, inadequate control for confounding variables, and small sample sizes within subgroups with reported associations). Review panels evaluating this initial body of research

[4] Selection bias arises if there are differences in the persons who participate in a study compared to the persons who do not participate in a study that are related to the exposure and differential by case/control status. For example, if the parents of a child with leukemia were informed that the study was investigating magnetic field exposure and they resided close to a transmission line, they may be more likely to participate than a family that lived far from a transmission line. As a result, children with leukemia that lived closer to transmission lines (and with a presumably higher magnetic field exposure) would be over-represented in the study population compared to the source population. In this scenario, the study may report that children with leukemia are more likely to have higher magnetic field exposure when, if the entire source population of leukemia cases were to be considered, there would be no difference in the exposure levels between leukemia cases and controls.

concluded that the evidence in support of an association was weak, but should be further evaluated with higher quality studies (NRPB, 2001; IARC, 2002; ICNIRP, 2003).

A large number of studies on breast cancer and magnetic field exposure have been conducted since the publication of the IARC review in 2002. These studies were systematically reviewed by the WHO and included seven studies that estimated residential magnetic field exposure, four studies reporting associations with electric blanket usage, and nine studies that estimated occupational magnetic field exposure. No consistent associations between magnetic field exposure and breast cancer were reported in these studies. The WHO concluded that this recent body of research was higher in quality compared with previous studies, and, for that reason, provides strong support to previous consensus statements that magnetic field exposure does not influence the risk of breast cancer. In summary, the WHO stated "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). The WHO recommended no further research with respect to breast cancer and magnetic field exposure.

Breast cancer has received additional attention because of some initial epidemiologic and experimental findings suggesting that magnetic fields may depress levels of the hormone melatonin (which is believed to have anti-carcinogenetic effects), leading to the development of breast cancer. A comprehensive weight-of-evidence review by the Health Protection Agency of Great Britain (HPA) in 2006 concluded that the evidence to date did not support the hypothesis that exposure to magnetic fields affects melatonin levels, or the risk of breast cancer in general (HPA, 2006). The WHO also considered this body of research, concluding "Overall, these data do not indicate that ELF electric and/or magnetic fields affect the neuroendocrine system in a way that would have an adverse impact on human health and the evidence is thus considered inadequate" (p. 186).

Adult leukemia and brain cancer

A large number of studies of variable quality and using a wide range of techniques have been conducted in both occupational and residential settings to explore the possible relationship between EMF exposure and adult brain cancer and leukemia. The scientific committees assembled by the IARC, NRPB, and ICNIRP concluded that the evidence is weak and does not support a role for electric or magnetic fields in the etiology of brain cancer or leukemia among adults (NRPB, 2001a; IARC, 2002; ICNIRP, 2003). The WHO reviewed the body of research published since the time of these reviews, including three studies estimating residential exposure, four cohort studies estimating occupational exposures, and eight case-control studies reported on occupation and brain cancer or leukemia risk. The WHO concluded, "In the case of adult brain cancer and leukaemia, the new studies published after the IARC monograph do not change the conclusion that the overall evidence for an association between ELF [EMF] and the risk of these disease remains inadequate" (p. 307). The WHO panel recommended updating the existing European cohorts of occupationally exposed individuals and then pooling the epidemiologic data on brain cancer and adult leukemia to confirm the absence of an association.

***In vivo* and *in vitro* research on carcinogenesis**

It is standard procedure to conduct studies of laboratory animals to determine whether exposure to a specific agent leads to the development of cancer (USEPA, 2005). This approach is used because all known human carcinogens cause cancer in laboratory animals. In the field of ELF EMF research, a number of research laboratories have exposed rodents with a particular genetic susceptibility to cancer to high levels of magnetic fields over the course of their lifetime and performed tissue evaluations to assess the incidence of cancer in many organs. In these studies, magnetic field exposure has been administered alone (to test for the ability of magnetic fields to act as a complete carcinogen), in combination with a known carcinogen (to test for a promotional or co-carcinogenetic effect), or in combination with a known carcinogen and a known promoter (to test for a co-promotional effect). The WHO described four large-scale, long-term studies of rodents exposed to magnetic fields over the course of their lifetime that did not report increases in any type of cancer (Mandeville et al., 1997; Yasui et al., 1997; Boorman et al., 1999a, 1999b; McCormick et al., 1999). No directly relevant animal model for childhood acute lymphoblastic leukemia (ALL) currently exists. Some animals, however, develop a type of lymphoma similar to

childhood ALL and studies exposing transgenic mice predisposed to this lymphoma to power-frequency magnetic fields have not reported an increased incidence of lymphoma associated with exposure (Harris et al., 1998; McCormick et al., 1998; Sommer and Lerchel 2004). Based on this body of research, the WHO panel concluded that exposure to ELF magnetic fields, does not appear to cause cancer alone, although it is a high priority to identify and perform studies on an animal model that is more directly relevant to childhood ALL.

Studies investigating whether exposure to magnetic fields can promote cancer or act as a co-carcinogen used known cancer-causing agents, such as ionizing radiation, ultraviolet radiation, or other chemicals. No effects were observed for studies on chemically-induced preneoplastic liver lesions, leukemia/lymphoma, skin tumors, or brain tumors; however, the incidence of DMBA-induced mammary tumors was increased with magnetic field exposure in a series of experiments (Löscher et al., 1993, 1994, 1997; Baum et al., 1995; Löscher and Mevissen, 1995; Mevissen et al., 1993a, 1993b, 1996a, 1996b, 1998), suggesting that magnetic field exposure increased the proliferation of mammary tumor cells. These results were not replicated in subsequent series of experiments in another laboratory (Anderson et al., 1999; Boorman et al.1999; NTP, 1999), possibly due to differences in experimental protocol and the species strain (Fedrowitz et al., 2004). Some studies have reported an increase in genotoxic effects among exposed animals (e.g., DNA strand breaks in the brains of mice [Lai and Singh, 2004]), although the results have not been replicated.

In summary, the WHO concluded with respect to *in vivo* 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." Recommendations for future research include the development of a rodent model for childhood ALL and the continued investigation of whether magnetic fields can act as a co-carcinogen.

In vitro studies are widely used to investigate the mechanisms for effects that are observed in humans and animals. The relative value of *in vitro* tests to human health risk assessment, however, is much less than that of *in vivo* and epidemiology studies. Responses of cells and tissues outside the body may not always reflect the response of those same cells if maintained in a living system, so the relevance of *in vitro* studies cannot be assumed (IARC, 1992).

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

Reproductive Effects

Epidemiology studies have been conducted to observe whether maternal or paternal EMF exposures are associated with adverse reproductive effects, including effects on fertility, reproduction, miscarriage, and prenatal and postnatal growth and development. A body of *in vivo* literature is also available on this topic. Early studies on the potential effect of EMF exposures on reproductive outcomes were limited because the majority of the studies used surrogate measures of exposure (including visual display terminal use, electric blanket use, or wire code data) or assessed exposure retrospectively.

Two recent studies related to miscarriage improved exposure assessment by directly measuring magnetic field exposure. These two studies reported a positive association between miscarriage and exposure to high maximum, or instantaneous, peak magnetic fields (Li et al., 2002; Lee et al., 2002). No consistent associations were reported, however, with high, average magnetic field

levels, the typical method for assessing magnetic field exposure. The WHO noted several issues that have been raised by other investigators and scientific review panels concerning the validity of these associations (HCN, 2004; NRPB, 2004; Feychting et al., 2005; Mezei et al., 2005; Savitz et al., 2006). First, the studies had a low response rate, which means that the case and control groups may not be comparable because those who participated in the study may have differed from those who declined (i.e., selection bias). Second, in the study by Lee et al. (2002), magnetic field measurements were taken 30 weeks after a woman's last menstrual period. Some of these women had already miscarried at 30 weeks when magnetic field exposure was measured. This introduces the possibility for bias because pregnancy may alter physical activity levels and physical activity may be associated with magnetic field exposure in pregnant women, as recently confirmed in a study by Savitz et al. (2006). It is possible that the women who miscarried prior to 30 weeks in the study by Lee et al. (2002) subsequently increased their physical activity levels (i.e., returned to work or their normal routine), which resulted in greater opportunities to encounter higher peak magnetic field levels. Furthermore, there is no biological basis to indicate that EMF increases the risk of reproductive effects. *In vivo* studies exposed animals to high levels of electric and magnetic fields and reported no significant, adverse developmental effects. The WHO stated that *in vivo* studies on other reproductive outcomes are inadequate at this time.

The WHO concluded that, overall, the body of research does not suggest that maternal or paternal exposures to ELF EMF cause adverse reproductive outcomes. The evidence from epidemiology studies on miscarriage is inadequate, and further research on this possible association is recommended, although low priority was given to this recommendation.

Neurodegenerative Diseases

Research into the possible effect of magnetic fields on the development of neurodegenerative diseases began in 1995, and the majority of research since then has focused on Alzheimer's disease and a specific type of motor neuron disease called amyotrophic lateral sclerosis (ALS) or Lou Gehrig's disease. The inconsistency of the Alzheimer's studies prompted the National Radiological Protection Board of Great Britain (NRPB)[5] to conclude that there is "only weak evidence to suggest that it [i.e., extremely low frequency magnetic fields] could cause Alzheimer's

[5] The NRPB merged with the Health Protection Agency in April 2005 to form its new Radiation Protection Division.

disease" (p. 20, NRPB, 2001b). Early studies on ALS, which had no obvious biases and were well conducted, reported an association between ALS mortality and estimated occupational magnetic field exposure. The review panels, however, were hesitant to conclude that the associations provided strong support for a causal relationship between ALS and occupational magnetic field exposure. The scientific panels felt that an alternative explanation (i.e., electric shocks received at work) may be the source of the observed association. The NRPB concluded: "In summary, the epidemiological evidence suggests that employment in electrical occupations may increase the risk of ALS, possibly, however, as a result of the increased risk of receiving an electric shock rather than from the increased exposure to electromagnetic fields" (p.20, NRPB, 2001b).

Most recent studies reported associations between occupational magnetic field exposure and mortality from Alzheimer's disease and ALS, although the design and methods of these studies were relatively weak (disease status based on death certificate data, exposure based on incomplete occupational information from census data, and no control for confounding factors). There is currently no biological data to support an association between magnetic fields and neurodegenerative diseases. The WHO concluded that there is inadequate data in support of an association between magnetic fields and Alzheimer's disease or ALS. The panel highly recommended that further studies be conducted in this area, particularly studies where the association between magnetic fields and ALS is estimated while controlling for the possible confounding effect of electric shocks.

References

Ahlbom A, Day N, Feychting M, Roman E, Skinner J, Dockerty J, Linet M, Michealis J, Olsen JH, Tynes T, Verasalo PK. A pooled analysis of magnetic fields and childhood leukaemia. British Journal of Cancer 83(5):692-698, 2000.

Anderson LE, Boorman GA, Morris JE, Sasser LB, Mann PC, Grumbein SL, Hailey JR, McNally A, Sills RC, Haseman JK. Effect of 13 week magnetic field exposures on DMBA-initiated mammary gland carcinomas in female Sprague-Dawley rats. Carcinogenesis 20:1615-1620, 1999.

Baum A, Mevissen M, Kamino K, Mohr U, Löscher W. A histopathological study on alterations in DMBA-induced mammary carcinogenesis in rats with 50 Hz, 100 muT magnetic field exposure. Carcinogenesis 16:119-125, 1995.

Boorman GA, Anderson LE, Morris JE, Sasser LB, Mann PC, Grumbein SL, Hailey JR, McNally A, Sills RC, Haseman JK. Effects of 26-week magnetic field exposure in a DMBA initiation-promotion mammary glands model in Sprague-Dawley rats. Carcinogenesis 20:899-904, 1999a.

Boorman GA, McCormick DL, Findlay JC, Hailey JR, Gauger JR, Johnson TR, Kovatch RM, Sills RC, Haseman JK. Chronic toxicity/oncogenicity evaluation of 60 Hz (power frequency) magnetic fields in F344/N rats. Toxicologic Pathology 27:267-78, 1999b.

Draper G, Vincent T, Kroll ME, Swanson J. Childhood cancer in relation to distance from high voltage power lines in England and Wales: a case-control study. BMJ 330 (7503):1290, 2005.

Elwood JM. Childhood leukemia and residential magnetic fields: are pooled analyses more valid than the original studies? Bioelectromagnetics 27:112-118, 2006.

Fedrowitz M, Kamino K, Löscher W. Significant differences in the effects of magnetic field exposure on 7,12-dimethylbenz(a)anthracene-induced mammary carcinogenesis in two substrains of Sprague-Dawley rats. Cancer Res 64:243-251, 2004.

Feychting M, Ahlbom A, Kheifets L. EMF and health. Annual Review of Public Health 26:165-89, 2005.

Greenland S, Sheppard A, Kelsh M, Kuane W, Poole C, Kelsh MA. Childhood leukemia and power frequency magnetic fields: analysis from pooled data of thirteen epidemiologic studies. Epidemiology 11:624-634, 2000.

Harris AW, Basten A, Gebski V, Noonan D, Finnie J, Bath ML, Bangay MJ, Repacholi MH. A test of lymphoma induction by long-term exposure of E mu-Pim1 transgenic mice to 50 Hz magnetic fields. Radiat Res 149(3):300-307, 1998.

Health Council of the Netherlands (HCN). ELF Electromagnetic Fields Committee. Electromagnetic fields: Annual Update 2003. The Hague: Health Council of the Netherlands. Publication No. 2004/1, 2004.

International Agency for Research on Cancer (IARC). Mechanisms of carcinogenesis in risk identification. No. 116. IARC Press, Lyon, France, 1992.

International Agency for Research on Cancer (IARC). IARC Monographs on the evaluation of carcinogenic risks to humans. Volume 80: Static and Extremely Low-Frequency (ELF) Electric and Magnetic Fields. IARC Press. Lyon, France, 2002.

International Commission on Non-Ionizing Radiation Protection (ICNIRP). Exposure to static and low frequency electromagnetic fields, biological effects and health consequences (0-100 kHz) – review of the scientific evidence on dosimetry, biological effects, epidemiological observations, and health consequences concerning exposure to static and low frequency electromagnetic fields (0-100 kHz). Matthes R, McKinlay AF, Bernhardt JH, Vecchia P, Beyret B (eds.). International Commission on Non-Ionizing Radiation Protection, 2003.

Ivancsits S, Diem E, Pilger A, Rudiger HW, Jahn O. Induction of DNA strand breaks by intermittent exposure to extremely-low-frequency electromagnetic fields in human diploid fibroblasts. Mutat Res 519(1- 2):1-13, 2002a.

Ivancsits S, Pilger A, Diem E, Schaffer A, Rudiger HW. Vanadate induces DNA strand breaks in cultured human fibroblasts at doses relevant to occupational exposure. Mutat Res 519(1-2):25-35, 2002b.

Ivancsits S, Diem E, Jahn O, Rudiger HW. Age-related effects on induction of DNA strand breaks by intermittent exposure to electromagnetic fields. Mech Ageing Dev 124(7):847-850, 2003a.

Ivancsits S, Diem E, Jahn O, Rudiger HW. Intermittent extremely low frequency electromagnetic fields cause DNA damage in a dose-dependent way. Int Arch Occup Environ Health 76(6):431-436, 2003b.

Kabuto M, Nitta H, Yamamoto S, Yamaguchi N, Akiba S, Honda Y, Hagihara J, Isaka K, Saito T, Ojima T, Nakamura Y, Mizoue T, Ito S, Eboshida A, Yamazaki S, Sokejima S, Kurokawa Y, Kubo O. Childhood leukemia and magnetic fields in Japan: a case-control study of childhood leukemia and residential power-frequency magnetic fields in Japan. Int J Cancer 119:643-650, 2006.

Lai H and Singh NP. Magnetic-field-induced DNA strand breaks in brain cells of the rat. Environ Health Perspect 112:687-694, 2004.

Lee G.M, Neutra RR, Hristova L, Yost M, Hiatt RA. The use of electric bed heaters and the risk of clinically recognized spontaneous abortion. Epidemiology 11:406-415, 2000.

Li DK, Odouli R, Wi S, Janevic T, Golditch I, Bracken TD, Senior R, Rankin R, Iriye R. A population-based prospective cohort study of personal exposure to magnetic fields during pregnancy and the risk of miscarriage. Epidemiology 13:9-20, 2002.

Linet MS, Hatch EH, Kleinerman RA, Robinson LL, Kaune WT, Friedman DR, Severs ch RK, Haines CM, Hartsock CT, Niwa S, Wacholder S, Tarone RE. Residential exposure to magnetic fields and acute lymphoblastic leukemia in children. New England Journal of Medicine 337:1-7, 1997.

Löscher W, Mevissen M, Lehmacher W, Stamm A. Tumor promotion in a breast cancer model by exposure to a weak alternating magnetic field. Cancer Lett 71:75-81, 1993.

Löscher W, Mevissen M. Linear relationship between flux density and tumor co-promoting effect of prolonged magnetic field exposure in a breast cancer model. Cancer Lett 96:175-180, 1995.

Löscher W, Mevissen M, Haussler B. Seasonal influence on 7,12-dimethylbenz[a]anthracene-induced mammary carcinogenesis in Sprague-Dawley rats under controlled laboratory conditions. Pharmacol Toxicol 81:265-270, 1997.

Mandeville R et al. Evaluation of the potential carcinogenicity of 60 Hz linear sinusoidal continuous-wave magnetic fields in Fisher F344 rats. FASEB-J, 11:1127-1136, 1997.

McBride ML, Gallagher RP, Thériault G, Armstrong BG, Tamaro S, Spinelli JJ, Deadman JE, Fincham S, Robinson D, Choi W. Power-frequency electric and magnetic fields and risk of childhood leukemia in Canada. American Journal of Epidemiology 149:831-842, 1999.

McCormick DL, Boorman GA, Findlay JC, Hailey JR, Johnson TR, Gauger JR, Pletcher JM, Sill RC, Haseman JK. Chronic toxicity/oncogenicity evaluation of 60 Hz (power frequency) magnetic fields in B6C3F mice. Toxicologic Pathology 27:279-285, 1999.

Mevissen M, Stamm A, Buntenkotter S, Zwingelberg R, Wahnschaffe U, Löscher W. Effects of magnetic fields on mammary tumor development induced by 7,12-dimethylbenz(a)anthracene in rats. Bioelectromagnetics 14:131-143, 1993a.

Mevissen M, Wahnschaffe U, Löscher W, Stamm A, Lerchl A. Effects of AC magnetic field on DMBA-induced mammary carcinogenesis in Sprague-Dawley rats. In: Electricity and Magnetism in Biology and Medicine. Blank M (ed). San Francisco Press. 413-415, 1993b.

Mevissen M, Lerchl A, Löscher W. Study on pineal function and DMBA-induced breastcancer formation in rats during exposure to a 100-mg, 50-Hz magnetic-field. J Toxicol Environ Health 48:169-185, 1996a.

Mevissen M et al. (1996). Exposure of DMBA-treated female rats in a 50-Hz, 50-μT magneticfield: effects on mammary-tumor growth, melatonin levels, and T-lymphocyte activation. Carcinogenesis 17:903-910, 1996b.

Mevissen M, Haussler M, Lerchl A, Löscher W. Acceleration of mammary tumorigenesis by exposure of 7,12-dimethylbenz[a]anthracene-treated female rats in a 50-Hz, 100-microT magnetic field: replication study. J Toxicol Environ Health A 53:401-418, 1998.

Mezei G, Bracken TD, Senior R, Kavet R. 2005. Examination of Magnetic-Field Peak-Exposure Measures. 27th Annual Meeting of the Bioelectromagnetics Society, Dublin, Ireland, June 19-24, 2005.

National Radiological Protection Board (NRPB). Response statement of the NRPB: ELF electromagnetic fields and the risk of cancer. National Radiological Protection Board, Chilton, Dicot, Oxon, Volume 12, No.1, ISNB 0-859951-456-0, 2001a.

National Radiological Protection Board (NRPB). ELF electromagnetic fields and neurodegenerative disease. National Radiological Protection Board. Volume 12, No 4, 2001b.

National Radiological Protection Board (NRPB). Review of the Scientific Evidence for Limiting Exposure to Electromagnetic Fields (0-300 GHz) National Radiological Protection Board, Volume 15, No 3, 2004.

National Research Council (NRC). An Evaluation of the U.S. Navy's Extremely Low Frequency Communications System Ecological Monitoring Program. National Academy Press, Washington, D.C., 1997.

Savitz DA, Herring AH, Mezei G, Evenson KR, Terry JW Jr, Kavet R. Physical activity and magnetic field exposure in pregnancy. Epidemiology 17:222-225, 2006.

Scarfi MR et al. Evaluation of genotoxic effects in human fibroblasts after intermittent exposure to 50 Hz electromagnetic fields: a confirmatory study. Radiat Res 164:270-276, 2005.

Sommer AM, Lerchl A. The risk of lymphoma in AKR/J mice does not rise with chronic exposure to 50 Hz magnetic fields (1 microT and 100 microT). Radiation Res 162:194-200, 2004.

United Kingdom Childhood Cancer Study Investigators (UKCCS). Exposure to power frequency magnetic fields and the risk of childhood cancer. The Lancet 353:1925-31, 1999.

US Environmental Protection Agency (USEPA). Guidelines for Carcinogen Risk Assessment and Supplemental Guidance for Assessing susceptibility from Early-life Exposure to Carcinogens. EPA/630/P-03/001F, 2005.

Wertheimer N and Leeper E. Electrical wiring configurations and childhood cancer. American Journal of Epidemiology 109:273-284, 1979.

World Health Organization (WHO). Environmental Health Criteria 238: Extremely Low Frequency (ELF) Fields. WHO, Geneva, Switzerland, ISBN 978-92-4-157238-5, 2007.

Yasui M, Kikuchi T, Ogawa M, Otaka Y, Tsuchitani M, Iwata H. Carcinogenicity test of 50 Hz sinusoidal magnetic fields in rats. Bioelectromagnetics 18:531-5400, 1997.

Appendix 2

WHO Fact Sheet

Fact sheet N°322
June 2007

Electromagnetic fields and public health
Exposure to extremely low frequency fields

The use of electricity has become an integral part of everyday life. Whenever electricity flows, both electric and magnetic fields exist close to the lines that carry electricity, and close to appliances. Since the late 1970s, questions have been raised whether exposure to these extremely low frequency (ELF) electric and magnetic fields (EMF) produces adverse health consequences. Since then, much research has been done, successfully resolving important issues and narrowing the focus of future research.

In 1996, the World Health Organization (WHO) established the International Electromagnetic Fields Project to investigate potential health risks associated with technologies emitting EMF. A WHO Task Group recently concluded a review of the health implications of ELF fields (WHO, 2007).

This Fact Sheet is based on the findings of that Task Group and updates recent reviews on the health effects of ELF EMF published in 2002 by the International Agency for Research on Cancer (IARC), established under the auspices of WHO, and by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) in 2003.

ELF field sources and residential exposures

Electric and magnetic fields exist wherever electric current flows - in power lines and cables, residential wiring and electrical appliances. **Electric** fields arise from electric charges, are measured in volts per metre (V/m) and are shielded by common materials, such as wood and metal. **Magnetic** fields arise from the motion of electric charges (i.e. a current), are expressed in tesla (T), or more commonly in millitesla (mT) or microtesla (μT). In some countries another unit called the gauss, (G), is commonly used (10,000 G = 1 T). These fields are not shielded by most common materials, and pass easily through them. Both types of fields are strongest close to the source and diminish with distance.

Most electric power operates at a frequency of 50 or 60 cycles per second, or hertz (Hz). Close to certain appliances, the magnetic field values can be of the order of a few hundred microtesla. Underneath power lines, magnetic fields can be about 20 μT and electric fields can be several thousand volts per metre. However, average residential power-frequency magnetic fields in homes are much lower - about 0.07 μT in Europe and 0.11 μT in North America. Mean values of the electric field in the home are up to several tens of volts per metre.

Task group evaluation

In October 2005, WHO convened a Task Group of scientific experts to assess any risks to health that might exist from exposure to ELF electric and magnetic fields in the frequency range >0 to 100,000 Hz (100 kHz). While IARC examined the evidence regarding cancer in 2002, this Task Group reviewed evidence for a number of health effects, and updated the evidence regarding cancer. The conclusions and recommendations of the Task Group are presented in a WHO Environmental Health Criteria (EHC) monograph (WHO, 2007).

Following a standard health risk assessment process, the Task Group concluded that there are no substantive health issues related to ELF electric fields at levels generally encountered by members of the public. Thus the remainder of this fact sheet addresses predominantly the effects of exposure to ELF magnetic fields.

Short-term effects

There are established biological effects from acute exposure at high levels (well above 100 μT) that are explained by recognized biophysical mechanisms. External ELF magnetic fields induce electric fields and currents in the body which, at very high field strengths, cause nerve and muscle stimulation and changes in nerve cell excitability in the central nervous system.

Potential long-term effects

Much of the scientific research examining long-term risks from ELF magnetic field exposure has focused on childhood leukaemia. In 2002, IARC published a monograph classifying ELF magnetic fields as "possibly carcinogenic to humans". This classification is used to denote an agent for which there is limited evidence of carcinogenicity in humans and less than sufficient evidence for carcinogenicity in experimental animals (other examples include coffee and welding fumes). This classification was based on pooled analyses of epidemiological studies demonstrating a consistent pattern of a two-fold increase in childhood leukaemia associated with average exposure to residential power-frequency magnetic field above 0.3 to 0.4 μT. The Task Group concluded that additional studies since then do not alter the status of this classification.

However, the epidemiological evidence is weakened by methodological problems, such as potential selection bias. In addition, there are no accepted biophysical mechanisms that would suggest that low-level exposures are involved in cancer development. Thus, if there were any effects from exposures to these low-level fields, it would have to be through a biological mechanism that is as yet unknown. Additionally, animal studies have been largely negative. Thus, on balance, the evidence related to childhood leukaemia is not strong enough to be considered causal.

Childhood leukaemia is a comparatively rare disease with a total annual number of new cases estimated to be 49,000 worldwide in 2000. Average magnetic field exposures above 0.3 μT in homes are rare: it is estimated that only between 1% and 4% of children live in such conditions. If the association between magnetic fields and childhood leukaemia is causal, the number of cases worldwide that might be attributable to magnetic field exposure is estimated to range from 100 to 2400 cases per year, based on values for the year 2000, representing 0.2 to 4.95% of the total incidence for that year. Thus, if ELF magnetic fields actually do increase the risk of the disease, when considered in a global context, the impact on public health of ELF EMF exposure would be limited.

A number of other adverse health effects have been studied for possible association with ELF magnetic field exposure. These include other childhood cancers, cancers in adults, depression, suicide, cardiovascular disorders, reproductive dysfunction, developmental disorders, immunological modifications, neurobehavioural effects and neurodegenerative disease. The WHO Task Group concluded that scientific evidence supporting an association between ELF magnetic field exposure and all of these health effects is much weaker than for childhood leukaemia. In some instances (i.e. for cardiovascular disease or breast cancer) the evidence suggests that these fields do not cause them.

International exposure guidelines

Health effects related to short-term, high-level exposure have been established and form the basis of two international exposure limit guidelines (ICNIRP, 1998; IEEE, 2002). At present, these bodies consider the scientific evidence related to possible health effects from long-term, low-level exposure to ELF fields insufficient to justify lowering these quantitative exposure limits.

WHO's guidance

For high-level short-term exposures to EMF, adverse health effects have been scientifically established (ICNIRP, 2003). International exposure guidelines designed to protect workers and the public from these effects should be adopted by policy makers. EMF protection programs should include exposure measurements from sources where exposures might be expected to exceed limit values.

Regarding long-term effects, given the weakness of the evidence for a link between exposure to ELF magnetic fields and childhood leukaemia, the benefits of exposure reduction on health are unclear. In view of this situation, the following recommendations are given:

- Government and industry should monitor science and promote research programmes to further reduce the uncertainty of the scientific evidence on the health effects of ELF field exposure. Through the ELF risk assessment process, gaps in knowledge have been identified and these form the basis of a new research agenda.
- Member States are encouraged to establish effective and open communication programmes with all stakeholders to enable informed decision-making. These may include improving coordination and consultation among industry, local government, and citizens in the planning process for ELF EMF-emitting facilities.
- When constructing new facilities and designing new equipment, including appliances, low-cost ways of reducing exposures may be explored. Appropriate exposure reduction measures will vary from one country to another. However, policies based on the adoption of arbitrary low exposure limits are not warranted.

Further reading

WHO - World Health Organization. Extremely low frequency fields. Environmental Health Criteria, Vol. 238. Geneva, World Health Organization, 2007.

IARC Working Group on the Evaluation of Carcinogenic Risks to Humans. Non-ionizing radiation, Part 1: Static and extremely low-frequency (ELF) electric and magnetic fields. Lyon, IARC, 2002 (Monographs on the Evaluation of Carcinogenic Risks to Humans, 80).

ICNIRP - International Commission on Non-Ionizing Radiation Protection. Exposure to static and low frequency electromagnetic fields, biological effects and health consequences (0-100 kHz). Bernhardt JH et al., eds. Oberschleissheim, International Commission on Non-ionizing Radiation Protection, 2003 (ICNIRP 13/2003).

ICNIRP – International Commission on Non-Ionizing Radiation Protection (1998). Guidelines for limiting exposure to time varying electric, magnetic and electromagnetic fields (up to 300 GHz). Health Physics 74(4), 494-522.

IEEE Standards Coordinating Committee 28. IEEE standard for safety levels with respect to human exposure to electromagnetic fields, 0-3 kHz. New York, NY, IEEE - The Institute of Electrical and Electronics Engineers, 2002 (IEEE Std C95.6-2002).

For more information contact:

WHO Media centre
Telephone: +41 22 791 2222
E-mail: mediainquiries@who.int

Appendix 3

Comment on the BioInitiative Report

Background

In August 2007, an *ad hoc* group of 14 scientists and public health and policy consultants published an on-line report titled "*The BioInitiative Report: A Rationale for a Biologically-based Public Exposure Standard for Electromagnetic Fields (ELF and RF)*." The group's objective was to "assess scientific evidence on health impacts from electromagnetic radiation below current public exposure limits and evaluate what changes in these limits are warranted now to reduce possible public health risks in the future" (p. 4). The individuals who comprised this group did not represent any well-established regulatory agency, nor were they convened by a recognized scientific authority. The report is a collection of 17 sections on various topics each authored by 1 to 3 persons from the working group. The research on both ELF and radio frequency (RF) EMF was addressed, with major portions of the report focused largely or entirely on RF research. Epidemiologic literature related to ELF EMF and childhood cancers, Alzheimer's disease, and breast cancer was discussed, as well as experimental data for a number of mechanistic hypotheses.

Conclusions and comments

The authors of the BioInitiative Report contended that the standard procedure for developing exposure guidelines—i.e., to set guidelines where adverse health effects have been established by using a weight-of-evidence approach—is not appropriate and should be replaced by a process that sets guidelines at exposure levels where biological effects have been reported in some studies, but not substantiated in a rigorous review of the science or linked to adverse health effects.

Based on this argument, the main conclusion of the BioInitiative Report was that existing standards for exposure to ELF EMF are insufficient because "effects are now widely reported to occur at exposure levels significantly below most current national and international limits" (Table 1-1). Specifically, the authors concluded that there was strong evidence to suggest that magnetic fields were a cause of childhood leukemia based on epidemiologic findings.

The report recommended the following:

> *ELF limits should be set below those exposure levels that have been linked in childhood leukemia studies to increased risk of disease, plus an additional safety factor … While new ELF limits are being developed and implemented, a reasonable approach would be a 1 mG (0.1 µT) planning limit for habitable space adjacent to all new or upgraded power lines and a 2 mG (0.2 µT) limit for all other new construction. It is also recommended that a 1 mG (0.1 µT) limit be established for existing habitable space for children and/or women who are pregnant. (p. 22)*

The recommendations made in the BioInitiative Report are not based on appropriate scientific methods and, therefore, do not warrant any changes to the conclusions from the numerous scientific agencies that have already considered this issue. These organizations are consistent in their conclusions that the research does not support the setting of exposure standards at these low levels of magnetic field exposure.

The World Health Organization (WHO) published the most recent weight-of-evidence review in June 2007 and concluded the following:

> *Everyday, low-intensity ELF magnetic field exposure poses a possible increased risk of childhood leukaemia, but the evidence is not strong enough to be considered causal and therefore ELF magnetic fields remain classified as possibly carcinogenic. (p. 357)*

The report continued:

> *Given the weakness of the evidence for a link between exposure to ELF magnetic fields and childhood leukaemia and the limited potential impact on public health, the benefits of exposure reduction on health are unclear and thus the cost of reducing exposure should be very low. (p. 372)*

The WHO made no recommendations for exposure standards at the magnetic field levels where an association has been reported in some epidemiologic studies of childhood leukemia. In a fact sheet created for the general public and published on their website, the WHO stated,

> *When constructing new facilities and designing new equipment, including appliances, low-cost ways of reducing exposures may be explored…However, policies based on the adoption of arbitrary low exposure limits are not warranted* (WHO, 2007b).

As stated, the conclusions in the BioInitiative Report deviate substantially from those of reputable scientific organizations because they were not based on standard, scientific methods. Valid

scientific conclusions are based on weight-of-evidence reviews, which entail a systematic evaluation of the entire body of scientific evidence in three areas of research (i.e., epidemiology, *in vivo* research, and *in vitro* research), by panels of experts in these relevant disciplines. The report by the BioInitiative working group does not represent a valid weight-of-evidence review for the following key reasons:

1. **Review panels should consist of a multidisciplinary team of experts that reach consensus statements by collaboratively contributing to and reviewing the final work product.** This process ensures that overall conclusions represent a valid and balanced view of each relevant area of research. The document released by the BioInitiative working group was a compilation of sections, with each authored by one to three members of the group. It does not appear that the report was developed collaboratively or reviewed in its entirety by each member.

2. **Valid conclusions about causality are based on systematic evaluations of three lines of evidence—epidemiology, *in vivo* research, and *in vitro* research.** The conclusions in the BioInitiative Report are not based on this multidisciplinary approach. In particular, little attention is provided to the results from *in vivo* studies on cancer and disproportionate weight is given to the results of *in vitro* studies reporting biological effects.

3. **The entire body of evidence to date should be considered when drawing conclusions regarding the strength of evidence in support of a hypothesis.** The BioInitiative Report is not a comprehensive review of the cumulative evidence. Rather, results from specific studies are cited, but no rationale is provided for their inclusion relative to the many other relevant, published studies.

4. **The evidence from each study must be evaluated critically to determine its validity and the degree to which it is relevant and able to support or refute the hypothesis under question.** The significance of the results reported in any study depends on the validity of the methods used in that study, so weight-of-evidence reviews must include an evaluation of the strengths and limitations of each study. In some discussions, the report claimed to use a weight-of-evidence approach, but the individual sections of the report provide little evidence that the strengths and limitations of individual studies (e.g., the quality of exposure assessment, sample size, biases, and confounding factors) were evaluated systematically.

5. **Support for a causal relationship is based on consistent findings from methodologically sound epidemiology studies that are coherent with the results reported from *in vivo* and *in vitro* studies**. The BioInitiative group often arrived at conclusions about causality by considering only a few studies from one discipline, with no consideration of the significance and validity of the study's results.

In summary, the authors of this report largely ignored basic scientific methods that should be followed in the review and evaluation of scientific evidence. These methods are fundamental to scientific inquiry and are not, as the BioInitiative Report states, "unreasonably high."

The policy responses proposed in the report are cast as consistent with the precautionary principle, i.e., taking action in situations of scientific uncertainty before there is strong proof of harm. A central tenet of the precautionary principle is that precautionary recommendations are proportional to the perceived level of risk and that this perception is founded largely on the weight of the available scientific evidence. The BioInitiative Report recommends precautionary measures on the basis of argument, rather than the basis of sound peer-reviewed scientific evidence.

Unlike the BioInitiative Report, the WHO review was the product of a multidisciplinary scientific panel assembled by an established public health agency that followed appropriate scientific methods, including the systematic and critical examination of all the relevant evidence. The recommendations from the WHO report (pp. 372-373) are presented below:

- *Policy-makers should establish guidelines for ELF field exposure for both the general public and workers. The best source of guidance for both exposure levels and the principles of scientific review are the international guidelines.*

- *Policy-makers should establish an ELF EMF protection programme that includes measurements of fields from all sources to ensure that the exposure limits are not exceeded either for the general public or workers.*

- *Provided that the health, social and economic benefits of electric power are not compromised, implementing very low-cost precautionary procedures to reduce exposures is reasonable and warranted.*

- *Policy-makers and community planners should implement very low-cost measures when constructing new facilities and designing new equipment including appliances.*

- *Changes to engineering practice to reduce ELF exposure from equipment or devices should be considered, provided that they yield other additional benefits, such as greater safety, or involve little or no cost.*

- *When changes to existing ELF sources are contemplated, ELF field reduction should be considered alongside safety, reliability and economic aspects.*

- *Local authorities should enforce wiring regulations to reduce unintentional ground currents when building new or rewiring existing facilities, while maintaining safety. Proactive measures to identify violations or existing problems in wiring would be expensive and unlikely to be justified.*

- *National authorities should implement an effective and open communication strategy to enable informed decision-making by all stakeholders; this should include information on how individuals can reduce their own exposure.*

- *Local authorities should improve planning of ELF EMF-emitting facilities, including better consultation between industry, local government, and citizens when siting major ELF EMF-emitting sources.*

- *Government and industry should promote research programmes to reduce the uncertainty of the scientific evidence on the health effects of ELF field exposure.*