Health Practice

Exponent®

Summary of the Current Status of Research on Health Effects of Electric and Magnetic Fields (EMF)

Prepared for:

The Town of Falmouth, Massachusetts

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Acronyms and Abbreviations

μT	Microtesla
AC	Alternating current
ADHD	Attention-deficit/hyperactivity disorder
AGNIR	Advisory Group on Non-ioinising Radiation
ALS	Amyotrophic lateral sclerosis
AMI	Acute myocardial infarction
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
CNS	Central nervous system
EFHRAN	European Health Risk Assessment Network on Electromagnetic Fields Exposure
ELF	Extremely low frequency
EMF	Electric and magnetic fields
Hz	Hertz
IARC	International Agency for Research on Cancer
ICES	International Committee on Electromagnetic Safety
ICNIRP	International Commission on Non-Ionizing Radiation Protection
mG	Milligauss
NIEHS	National Institute for Environmental and Health Sciences
NZMH	New Zealand Ministry of Health
SCENIHR	Scientific Committee on Emerging and Newly Identified Health Risks
SSM	Swedish Radiation Safety Authority
WHO	World Health Organization

Limitations

At the request of the town of Falmouth, Massachusetts, Exponent, Inc.,[1] prepared this summary report on the status of research related to power-frequency electric- and magnetic-field exposure and health, to assist the town in its review of the Mayflower Wind Project, a set of onshore transmission facilities that will be used to interconnect up to 1,200 megawatts of renewable energy to the New England bulk power grid in Falmouth, Massachusetts. The findings presented herein are made to a reasonable degree of scientific certainty. This report is limited to the papers reviewed and may not include all information in the public domain. Exponent reserves the right to supplement this report and to expand or modify opinions based on review of additional material as it becomes available, through any additional work, or review of additional work performed by others.

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

[1] See Appendix A for short biographies of the Exponent consultants who prepared this report.

Introduction

Electric and magnetic fields (EMF) are produced by both natural and man-made sources that surround us in our daily lives. Natural sources of EMF include the electric fields created by the normal functioning of our nervous and cardiovascular systems and the earth's static magnetic field. Man-made EMF are found wherever electricity is generated, transmitted, or used; sources of EMF include electrical appliances, power tools, the wiring in our homes and buildings, and transmission and distribution lines. Most electricity in North America is transmitted as alternating current (AC) at a frequency of 60 Hertz (Hz) (i.e., it changes direction and magnitude in a continuous cycle that repeats 60 times per second).[2] The fields from these AC sources are commonly referred to as power-frequency or extremely low frequency (ELF) EMF, which are in the range of the electromagnetic spectrum that includes frequencies up to 300 Hz (ICNIRP, 1998).

Since electricity is such an integral part of our infrastructure and everyday life, people living in modern communities are constantly exposed to EMF. While the intensity of EMF levels diminishes with increasing distance from the source, any buildings in our communities (e.g., homes, schools, offices) tend to have a background EMF level contributed by numerous sources of ELF EMF.[3] Over the past 50 years, researchers have been examining whether exposure to ELF EMF from these man-made sources can cause short- or long-term health effects in humans.

Exponent was requested by the Town of Falmouth, Massachusetts, to summarize the current research on ELF EMF and human health. The purpose of this report is to provide a short summary of the scientific reviews published by scientific and health agencies that have reviewed and evaluated the relevant research on EMF exposure and health. Research that has been published since the release of the most recent agency reviews will be briefly summarized to assess the impact of these studies on the conclusions reached by the reviewing agencies. The report also includes a brief discussion of applicable regulatory standards and exposure guidelines established for EMF.

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[2] Electrical power systems in many countries outside North America operate at a frequency of 50 Hz.

[3] Note, while ELF EMF fields from different sources may interact, they are independent of fields at other frequencies, including the static fields of the earth or radiofrequency fields from communication sources.

Summary of Agency Reviews

Scientific research on ELF EMF and human health has considered many aspects of physiology and diseases, including cancers in children and adults, neurodegenerative diseases, reproductive effects, and cardiovascular disease. This research is reviewed regularly by independent scientific and governmental organizations worldwide, which have assembled expert panels with the relevant expertise to conduct reviews of the scientific literature and provide scientifically-grounded public health recommendations. When conducting these reviews, the expert panels consider all the evidence on a particular issue in a systematic and thorough manner to evaluate whether the overall data presents a logically coherent and consistent picture. This is often referred to as a *weight-of-evidence review*, in which all research studies are considered together, giving more weight to studies of higher quality, and using an established analytic framework to arrive at a conclusion about possibly causality between an exposure and disease. The weight-of-evidence review process systematically evaluates individual studies on the basis of study relevance and quality, establishing a consistent and transparent selection and review procedure.

Over the past 30 years, numerous national and international scientific and health agencies have reviewed the research and evaluated potential health risks of exposure to ELF EMF. Recent reviews by such organizations include the World Health Organization (WHO), the International Agency for Research on Cancer (IARC), the U.S. National Institute for Environmental and Health Sciences (NIEHS), the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), the Advisory Group on Non-ionising Radiation (AGNIR), the International Commission on Non-Ionizing Radiation Protection (ICNIRP), the U.S. National Academy of Sciences, the European Health Risk Assessment Network on Electromagnetic Fields Exposure (EFHRAN), the European Commission's Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR), the New Zealand Ministry of Health (NZMH), and the Swedish Radiation Safety Authority (SSM) (NAS, 1997, 1999, AGNIR, 2001; IARC, 2002; NIEHS, 1999; WHO, 2007; ICNIRP, 2010; EFHRAN, 2012; SCENIHR, 2015; NZHM, 2015; SSM, 2016, 2018, 2019, 2020, 2021).

Overall, the published conclusions of the reviewing scientific and health agencies have been consistent. None have concluded that either electric fields or magnetic fields cause or contribute to any adverse health effects, including cancer or other chronic diseases, at the low exposure levels found in the environment. The overall conclusions of the scientific review panels convened for the WHO and SCENIHR, both of which conducted comprehensive reviews of the research, are further summarized below. Conclusions related to specific health outcomes, including child and adult cancers, are summarized in the next section of this report (*see* Summary of Recent Research).

World Health Organization

The WHO is a scientific organization within the United Nations system with the mandate to provide leadership on global health matters, shape health research agendas, and set norms and standards. A comprehensive review of ELF EMF research was published by the WHO in 2007 as their *Environmental Health Criteria Monograph 238* (WHO, 2007). The WHO's Task Group critically reviewed the cumulative epidemiologic and laboratory research through 2005, taking into account the strength and quality of the individual research studies. The 2007 WHO report concluded that ELF EMF was *possibly carcinogenic to humans*,[4] confirming the classification previously assigned by IARC in their 2002 review (IARC, 2002).

The WHO 2007 report provided the following overall conclusions:

> *New human, animal, and in vitro studies published since the 2002 IARC Monograph, 2002* [*sic*] *do not change the overall classification of ELF as a possible human carcinogen* (WHO, 2007, p. 347).
>
> *Acute biological effects [i.e., short-term, transient health effects such as a small shock] have been established for exposure to ELF electric and magnetic fields*

[4] The category *possibly carcinogenic to humans* denotes exposures for which there is *limited evidence of carcinogenicity* in epidemiologic studies and less than sufficient evidence of carcinogenicity in studies of experimental animals. *Limited evidence of carcinogenicity* describes a body of epidemiologic research where the findings are inconsistent or there are outstanding questions about study design or other methodological issues that preclude making a conclusion. The category *possibly carcinogenic to humans* is the lowest category used by WHO that denotes some evidence of carcinogenicity; categories are intentionally meant to err on the side of caution, giving more weight to the possibility that the exposure is truly carcinogenic and less weight to the possibility that the exposure is not carcinogenic. Other agents that are currently classified as *possibly carcinogenic* include gasoline, aloe vera, and pickled vegetables (traditional Asian).

> *in the frequency range up to 100 kHz that may have adverse consequences on health. Therefore, exposure limits are needed. International guidelines exist that have addressed this issue. Compliance with these guidelines provides adequate protection. Consistent epidemiological evidence suggests that chronic low-intensity ELF magnetic field exposure is associated with an increased risk of childhood leukaemia. However, the evidence for a causal relationship is limited, therefore exposure limits based upon epidemiological evidence are not recommended, but some precautionary measures are warranted* (WHO, 2007, p. 355).

The current guidance from the WHO on its website states:

> *Despite the feeling of some people that more research needs to be done, scientific knowledge in this area [of electromagnetic fields] is now more extensive than for most chemicals. Based on an in-depth review of the scientific literature* [*2007*]*, the WHO concluded that current evidence does not confirm the existence of any health consequences from exposure to low level electromagnetic fields. However, some gaps in knowledge about biological effects exist and need further research.*[5]

Scientific Committee on Emerging and Newly Identified Health Risks

The most recent weight-of-evidence review of EMF and health was released in 2015 by SCENIHR. The Committee consists of independent scientific experts assembled to provide advice on public health and risk assessments to the Department of Health and Consumer Protection of the European Commission. The Committee addresses questions related to emerging or newly identified health and environmental risks and on broad, complex, or multidisciplinary issues requiring a comprehensive assessment of risks to consumer safety or public health. The 2015 report on the potential health effects of exposure to EMF serves as an update to their previous review published in 2009 (SCENIHR, 2009). In performing its assessment of the literature, the Committee followed the scientific guidelines it developed to assess the quality of evidence of human health risks (SCENIHR, 2012).

[5] https://www.who.int/news-room/questions-and-answers/item/radiation-electromagnetic-fields. Accessed March 3, 2022.

The conclusions of the 2015 SCENIHR review are consistent with earlier comprehensive reviews, most notably the WHO review discussed above. The scientific evidence reviewed in SCENIHR (2015) did not confirm a causal link between any adverse health effects (including both cancer and non-cancer health outcomes) and EMF exposure.

Summary of Recent Research

This section summarizes the results of recent epidemiologic research[6] on specific health conditions investigated in relation to ELF EMF and discusses whether the results of these recent studies alter the conclusions of the WHO (2007) or SCENIHR (2015) reports.

The focus of this report is on EMF from transmission of 60-Hz electricity, so only studies of ELF EMF are included since they are directly relevant to assessing the potential biological and health effects of EMF at this frequency.[7] Although health and scientific agencies draw conclusions about potential health risks based on assessments of all three broad classifications of research studies—epidemiologic observations of people, experimental laboratory studies of humans and animals (*in vivo*), and experimental laboratory studies of cells and tissues (*in vitro*) —this report focuses on human epidemiologic studies, which have reported associations with magnetic-field exposure and various health conditions in some studies.

Childhood Leukemia

Since the late 1970s, numerous epidemiologic studies have evaluated the relationship between exposure to ELF EMF and childhood leukemia. In their 2002 review, IARC classified EMF as *possibly carcinogenic* largely as a result of two combined analyses of epidemiologic studies that reported an association between childhood leukemia and estimates of exposure to daily average magnetic-field levels greater than 3-4 milligauss [mG]) (Ahlbom et al., 2000; Greenland et al., 2000). The classification of *possibly carcinogenic* was confirmed by the WHO in their 2007 review, in which the WHO concluded that the *"evidence for a causal relationship [between ELF magnetic-field exposure and childhood leukemia] is limited"* (WHO, 2007, p. 355). Similarly, SCENIHR concluded in their 2015 report that *"no mechanisms have been identified and no support is existing from experimental studies that could explain these findings, which, together*

[6] Relevant peer-reviewed epidemiologic research studies are included that were published on of before December 2021.

[7] The major focus of the review is magnetic-field exposure. Research has focused on magnetic fields because, among other reasons, conductive objects effectively shield electric fields, and power lines have little effect on the potential long-term, average electric-field exposure of nearby residents.

with shortcomings of the epidemiological studies prevent a causal interpretation" (SCENIHR, 2015, p.7).

More recently, several large epidemiologic studies from various countries, including France (Sermage-Faure et al., 2013), Denmark (Pedersen et al., 2014a, 2014b, 2015), the United Kingdom (Bunch et al., 2014, 2015, 2016), the United States (Crespi et al., 2016, 2019; Kheifets et al., 2017; Amoon et al., 2018a, 2019, 2020), and Canada (Auger et al., 2019a), have assessed the potential risk of childhood leukemia in relation to either residential proximity to high-voltage power lines or calculated magnetic-field exposure.[8] None of these studies reported consistent overall associations between the development of childhood leukemia and distance to transmission or distribution or lines or calculated magnetic-field levels. One of the largest of these studies (Bunch et al., 2014) included over 53,000 childhood cancer cases diagnosed between 1962 and 2008 and served as an update to an earlier analysis of the same study population (Draper et al., 2005). The authors in Bunch et al. (2014) noted that a previous association between childhood leukemia and proximity to power lines observed in the earlier study (Draper et al., 2005) was no longer observed in the 2014 updated analysis. This led the authors to conclude that the observed declining risk "*almost certainly cannot be produced by powerline-generated magnetic fields*" (Bunch et al., 2014, p. 1407). Additional recent epidemiologic studies, conducted in diverse countries and using a variety of study designs and exposure assessment methods, also did not report consistent associations between magnetic-field exposures and childhood leukemia (Magnani et al., 2014; Salvan et al., 2015; Kyriakopoulou et al., 2018; Núñez-Enríquez et al., 2021).

Several pooled analyses and meta-analyses of research related to EMF and childhood leukemia have also been conducted in recent years.[9] Kheifets et al. (2010) provided an update to the Ahlbom et al. (2000) and Greenland et al. (2000) studies by reporting the results of a pooled

[8] An important limitations of many of the studies discussed in this section, and throughout this report, is the use of residential distance to power lines as the main exposure metric, which is considered to be a poor predictor of actual residential magnetic-field exposure (e.g., Bonnet-Belfais et al., 2013; Clavel et al., 2013; Chang et al., 2014).

[9] Pooled analyses combined the raw, individual-level data from original epidemiologic studies and analyze the data altogether, therefore increasing the number of individuals in the analysis and allowing for a more robust and stable estimate of association. Meta-analysis is an analytic technique that combines the published summary results from a group of studies into one summary result. Similar to pooled analyses, it is an important tool for qualitatively synthesizing the results of a large group of studies.

analysis of seven epidemiologic studies of childhood leukemia and measured and calculated ELF magnetic fields published between 2000 and 2010. The study by Kheifets et al. (2010) reported a moderate and statistically not significant association[10] for the highest exposure category, which was weaker than the association reported in the previous analyses (Ahlbom et al., 2000; Greenland et al., 2000). Amoon et al. (2022) conducted a pooled analysis that included data from epidemiologic studies of residential exposure to magnetic fields and childhood leukemia published after the Kheifets et al. (2010) analysis; Amoon et al. (2022) concluded, "*our results do not show the risk increase observed in previous pooled analysis and, over time, show a decrease in effect to no association between MF [magnetic fields] and childhood leukemia.*" Several recently conducted meta-analyses of epidemiologic studies of childhood leukemia and exposure to magnetic fields reported no consistent associations (Amoon et al., 2018b; Swanson et al., 2019; Talibov et al., 2019).

Seomun et al. (2021) performed a meta-analysis of case-control studies investigating the potential relationship between ELF magnetic fields and childhood cancer and reported statistically significant associations between childhood leukemia and magnetic-field exposures of 0.2 microtesla (μT) (2 milligauss [mG]) and 0.4 μT (4 mG), while the relationship to magnetic-field exposures of 0.3 μT (3 mG) was not statistically significant. The statistically significant associations observed in Seomun et al. (2021) are likely driven by the small number studies that reported large non-statistically significant associations, even though the majority of the included studies reported small (i.e., close to 1.0) or no associations.

In summary, most of the recently published large and methodologically improved studies showed no statistically significant associations between estimates of magnetic-field exposures and childhood leukemia. However, the association observed in some earlier studies remains unexplained. Thus, the recent literature does not alter the previous conclusions of the WHO report, SCENIHR report, and other reviews that the epidemiologic evidence on magnetic fields

[10] The terms statistically significant or statistically significant association are used in epidemiologic studies to describe the tendency of the level of exposure and the occurrence of disease to be linked, with chance as an unlikely explanation. Statistically significant associations, however, are not necessarily an indication of cause-and-effect because the interpretation of statistically significant associations depends on many other factors associated with the design and conduct of the study besides sampling error, including the number of study participants, systematic bias and error, how the data were collected and analyzed, and confounding factors.

and childhood leukemia is *limited*, weak, and inconsistent, and includes outstanding questions about study design or other methodological issues (Kheifets and Oksuzyan, 2008; Pelissari et al., 2009; Schüz and Ahlbom, 2008; Calvente et al., 2010; Eden, 2010; Schüz, 2011).

Childhood Brain Cancer

Compared to the research on magnetic fields and childhood leukemia, there have been fewer studies of childhood brain cancer, and the WHO has noted that "*the evidence for other childhood cancers* [*besides leukemia*] *remains inadequate*" (WHO, 2007, p. 307). Several of the epidemiologic studies of childhood leukemia discussed above also investigated the potential relationship between residential proximity to overhead and underground transmission lines and childhood brain cancer (Bunch et al., 2014, 2015, 2016; Pedersen et al., 2015; Crespi et al., 2016; Auger et al., 2019a). None of these studies reported any consistent association between distance to power lines and development of childhood brain cancer. The meta-analysis performed by Seomun et al. (2021) reported non-statistically significant associations between childhood brain tumors and ELF magnetic fields at both exposure levels examined—0.2 μT (2 mG) and 0.4 μT (4 mG). In addition, Su et al. (2018) conducted a meta-analysis of epidemiologic studies that investigated the association between parental occupational exposure to ELF magnetic fields and childhood central nervous system (CNS) tumors. The authors reported a weak statistically significant association between maternal exposure to ELF magnetic fields and childhood CNS tumors, but concluded that the results "*provide limited evidence*" for an association, "*which should be explained with cautions* [*sic*]" (Su et al., 2018, p. 1413).

In summary, the weight-of-evidence does not support an association between ELF EMF and the development of childhood brain cancer, as none of the recent studies reported any consistent and convincing evidence for an association. This is in line with the SCENIHR (2015) review, which concluded that "*no association has been observed for the risk of childhood brain tumours*" (SCENIHR, 2015, p. 158).

Breast Cancer

In their 2007 report, the WHO reviewed studies of breast cancer and residential and occupational magnetic-field exposure, as well as electric blanket usage. The WHO noted that these studies, which did not report consistent associations between magnetic-field exposure and breast cancer, were less susceptible to bias compared with earlier studies published prior to the IARC (2002) review, and as a result, "*the evidence for an association between ELF exposure and the risk of breast cancer [was] weakened considerably and [did] not support an association of this kind"* (WHO, 2007, p. 307). The recent review by SCENIHR (2015) concluded that overall, studies on "*adult cancers show no consistent associations*" (p. 158).

Subsequent research has provided additional support for the WHO's conclusion that there is no association between exposure to ELF EMF and breast cancer development. A large epidemiologic study that investigated the risk of several types of adult cancers and residential distance to high-voltage power lines reported no association between female breast cancer and distance to power lines or estimated exposure to magnetic fields (Elliott et al., 2013). Several occupational epidemiologic studies of female and male breast cancers also provided no support for an association between ELF EMF exposure and breast cancer development (Sorahan, 2012, 2019; Li et al., 2013; Koeman et al., 2014; Grundy et al., 2016). The most recent of these studies[11] (Grundy et al., 2016), reported no statistically significant associations between occupational exposure to EMF and male breast cancer. Together, these studies add to the growing body of evidence against a role for magnetic-field exposure in breast cancer development in either residential or occupational settings.

Adult Brain Cancer

The 2007 WHO report noted that the findings for adult brain cancer, which was studied in many of the occupational studies of ELF EMF, were inconsistent, although a small association could not be ruled out. The WHO classified the epidemiologic data on adult brain cancer as *inadequate* (WHO, 2007). Subsequent epidemiologic studies of ELF EMF and adult brain

[11] No published epidemiologic studies examining the potential relationship between ELF EMF exposure and breast cancer development have been identified since the Grundy et al. (2016) publication.

cancer predominantly support no association, but remain limited due to weaknesses in exposure assessment methods and insufficient data available on specific brain cancer subtypes. As mentioned above, the most recent SCENIHR report states that, overall, studies on "*adult cancers show no consistent associations*" (SCENIHR, 2015, p. 158).

Several recent studies of occupational exposure to ELF EMF observed no overall association between exposure and the development of glioma (Carlberg et al., 2017), meningioma (Carlberg et al., 2018), or acoustic neuroma (Carlberg et al., 2020). In the glioma study by Carlberg et al. (2017), the authors conducted several sub-group analyses,[12] including analyses by tumor type and exposure time period. An association was reported for a specific subtype of glioma (grade IV astrocytoma) when the analysis was restricted to exposure experienced during the more recent time period (1 to 14 years prior to diagnosis); however, the authors reported no association with more distant exposure periods (15 to 20+ years) and observed no associations for other tumor grades (Carlberg et al., 2017). The authors hypothesized that the observed association for grade IV astrocytoma in the recent exposure periods was the result of a potential effect on cancer promotion, but there is no supporting evidence for this hypothesis from other epidemiologic or experimental studies.

Carles et al. (2020) investigated the association between residential proximity to power lines and brain tumor development among adults in France. Several statistically significant associations were reported; however, the associations were not consistent across brain tumor types or exposure metrics, and no clear exposure-response trend was observed. Souques et al. (2020) highlighted several methodological limitations in the Carles et al. (2020) study, including the potential for exposure misclassification due to inaccuracies of the geolocation method used to ascertain residential distance to power lines and the study's failure to account for underground

[12] In addition to the main analyses, researchers may also conduct sub-group analyses of the data, in which subsets, or groups, of the study population are analyzed separately based on one or more shared characteristics (e.g., tumor sub-type, length of exposure duration, gender, age, etc.). The goal of sub-group analyses is to examine if and how the relationship between the exposure and outcome of interest varies across different subsets of the population, and sub-group analyses can sometimes lead to additional research questions that should be explored in future studies. However, sub-group analyses are generally considered secondary to the main analyses and should always be interpreted with caution, as they typically include fewer study participants per group and may represent *post hoc* attempts by researchers to identify any statistically significant associations in the data when none were observed in the main analyses (Fletcher, 2007; Wang et al., 2007).

lines, which would result in lower exposure levels. Souques et al. (2020) concluded that due to these limitations, the results of the Carles et al. (2020) study were *"meaningless and unusable"* (Souques et al., 2020, p. 2).

Khan et al. (2021) examined the relationship between magnetic-field exposure and brain tumor development among Finnish residents living in buildings with indoor transformer stations. Exposure to magnetic fields was assessed using the location of the participants' apartment in relation to the location of the transformer station. The authors reported no association between magnetic-field exposure and meningioma based on residential location, and a non-statistically significant association with glioma. No association was reported between brain tumors and duration of residence near transformers.

In summary, recent studies do not provide support for a causal association between exposure to magnetic fields and brain cancer development, and as with breast cancer, are consistent with the conclusions of the most recent review by SCENIHR (2015).

Adult Leukemia and Lymphoma

There is vast literature on ELF EMF and adult leukemia, most of which is related to occupational exposure. Overall, the findings of these studies are inconsistent—some studies report a positive association between measures of ELF EMF and leukemia and other studies show no association. In their 2007 review, the WHO classified the epidemiologic evidence for adult leukemia as *inadequate*.

Recent studies do not provide substantial evidence for an association between ELF EMF and leukemia (overall or sub-types) or lymphoma in adults. Talibov et al. (2015) conducted a study of acute myeloid leukemia and occupational exposure to ELF magnetic fields and electric shocks. The authors reported no associations between leukemia and exposure to ELF magnetic fields or electric shocks among either men or women, and the authors concluded that "*the evidence base linking ELF-MF* [*magnetic fields*] *with AML* [*acute myeloid leukemia*] *risk remains weak*" (Talibov et al., 2015, p. 1084).

Huss et al. (2018a) examined occupational exposure to ELF magnetic fields and death from several types of hematopoietic malignancies (leukemias and lymphomas) among adults in Switzerland who participated in the country's 1990 or 2000 census, or both. None of the hematopoietic cancer types included in the main analyses were statistically associated with magnetic-field exposure. The authors hypothesized that the associations observed in some of the sub-analyses may be due to the lack of information on lifestyle factors, such as smoking, which is a well-established cause of leukemias and lymphomas. In the same study, the authors also conducted a meta-analysis of epidemiologic studies of occupational exposure to ELF magnetic fields and acute myeloid leukemia and reported a weak overall association. The authors concluded that the study's findings "*provided no convincing evidence for an increased risk of death*" from hematopoietic cancers in workers occupationally exposed to ELF magnetic fields (Huss et al., 2018a, p. 467).

The study by Khan et al. (2021), previously described in the section on adult brain cancer, also examined magnetic-field exposures (based on residential distance from the nearest transformer stations) and hematological neoplasms, including lymphoma and leukemia. A statistically significant association was reported for acute lymphocytic leukemia, based on only four exposed cases. No associations were reported for other leukemia subtypes or for lymphoma or multiple myeloma. Odutola et al. (2021) conducted a systematic review and meta-analysis of various occupational exposures and follicular lymphoma, a common non-Hodgkin lymphoma subtype. Only two studies were identified that specifically investigated occupational ELF magnetic-field exposure (Koeman et al., 2014; Huss et al., 2018a); no consistent pattern was observed in these studies.

In summary, the previous conclusion that the evidence for adult leukemia is *inadequate* remains appropriate. While some scientific uncertainty remains on a potential relationship between adult lymphohematopoietic malignancies and magnetic-field exposure because of continued deficiencies in study methods, the current research does not provide sufficient evidence for an association (EFHRAN, 2012; SCENIHR, 2015).

Reproductive and Developmental Effects

In 2002, prior to the WHO report, 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). However, limitations of these studies prevented scientific panels, including the WHO, from making any conclusions about the effect of magnetic fields on miscarriage (NRPB, 2004; FPTRPC, 2005; WHO, 2007). In their 2007 report, the WHO concluded, "*[t]here is some evidence for increased risk of miscarriage associated with measured maternal magnetic-field exposure, but this evidence is inadequate*" (WHO, 2007, p. 254). The most recent review by SCENIHR concluded that "*recent results do not show an effect of ELF MF* [*magnetic field*] *exposure on reproductive function in humans*" (SCENIHR, 2015).

Recent research on ELF EMF exposure and reproductive or development effects includes studies focusing on female infertility, miscarriage, stillbirth, pre-term birth, and birth outcomes or defects (Auger et al., 2012; Mahram and Ghazavi, 2013; Wang et al., 2013; Shamsi Mahmoudabadi et al., 2013; de Vocht et al., 2014; Eskelinen et al., 2016; Li et al., 2017; Sadeghi et al., 2017; Sudan et al., 2017; Migault et al. 2018; Auger et al., 2019b; Esmailzadeh et al., 2019; Ren et al., 2019; Ingle et al., 2020; Li et al., 2020a; Zarei et al., 2019; Zhao et al., 2021). Overall, these studies do not provide substantial new evidence in support of an associated between EMF and reproductive or developmental outcomes. Li et al. (2017) examined the association between magnetic-field exposure and miscarriage using 24-hour personal magnetic-field measurements collected on a single day during pregnancy. The authors reported an increased risk of miscarriage in women with high magnetic-field exposure (i.e., the 99th percentile value during the 24-hour measurement of ≥2.5 mG) compared to women with low magnetic-field exposure (<2.5 mG) when measurements were collected on a subject-reported typical day of pregnancy. They reported no association, however, among those women whose exposure was measured on a non-typical day, and no trend was observed for miscarriage risk with increasing magnetic-field exposure >2.5 mG. While personal exposure measurements are an improvement over some of the earlier studies, the collection of only one measurement over a single 24-hour period during pregnancy is a limitation of the Li et al. (2017) study, as day-to-day

changes in exposure cannot be captured. Additional limitations include the absence of information on whether the measurements were taken before or after the occurrence of miscarriage and the failure to measure mobility during the measurement day, which is expected to vary between women with healthy pregnancies and women who have a miscarriage (Savitz, 2002; Mezei et al., 2006; Savitz et al., 2006). Grimes and Heathers (2021) published an evaluation of the Li et al. (2017) paper and concluded that "*this work exemplifies a number of deeply unsound methodological choices that nullify its strong conclusion*" (Grimes and Heathers, 2021, p.1). The limitations discussed by Grimes and Heathers (2021) include the exclusion of over half of the study population resulting in disproportional selection of subjects by exposure status, and the inappropriate dichotomization of the data.

In a subsequent study on the same population, Li et al. (2020a) assessed whether maternal exposure to magnetic fields was associated with the development of attention-deficit/hyperactivity disorder (ADHD) in their offspring. For this analysis, the authors selected the 90th percentile value observed during the 24-hour measurement period as the exposure of interest, rather than the 99th percentile value previously used in Li et al. (2017). The authors reported a statistically significant association between mothers exposed to high levels of magnetic fields (defined as ≥1.3 mG) and a diagnosis of ADHD in their offspring; a stronger association was observed for children with a diagnosis persisting into adolescence. As noted above, the collection of only one measurement over a single 24-hour period during pregnancy is a limitation of this exposure assessment approach. Further, the specific exposure metrics and cut-points used in both studies are unconventional and have not typically been used in previous epidemiologic studies investigating potential health effects of EMF. The authors' unorthodox decision to use a cut-point of 1.3 mG or higher to define a high maternal exposure level in Li et al. (2020a) was called into question by others in the research community for being poorly defined and explained by the authors. As a result, in February 2021, the primary author of the Li et al. (2020a) paper issued a notice of retraction and replacement for the study, based on "*errors in the statistical analyses*," and re-analyzed the study data using newly defined exposure levels (Li, 2021). In the revised study, which was published as Supplement 3 to the original 2020

article, the authors concluded that the revised associations "*were inconsistent and nonlinear*" and thus "*the results should be interpreted with caution*" (Li et al., 2020b, p. 10).[13]

Migault et al. (2020) conducted a pooled analysis of two French studies (Vandentorren et al., 2009; Ancel et al., 2014) to examine the relationship between maternal cumulative exposure to magnetic fields during pregnancy and the risk of prematurity or small for gestational age. The authors reported no association between cumulative magnetic-field exposure and prematurity for the two highest exposure categories; conversely, an increased risk of prematurity was observed for the lower exposure category. No consistent associations were observed between cumulative magnetic-field exposure and the small for gestational age outcome. The authors concluded that "*due to the heterogeneity of the results regarding exposure levels, the associations observed cannot be definitely explained by ELF-EMF exposure*" (Migault et al., 2020, p. 27).

In summary, recent publications provide little new insight on pregnancy and reproductive outcomes and do not change the classification of the data from earlier assessments as *inadequate*. Studies in this research area continue to suffer from limitations in study design, sample size, and exposure assessment method, which may explain the inconsistent findings (Lewis et al., 2016).

Neurodegenerative Diseases

Research into the possible effect of magnetic fields on the development of neurodegenerative diseases began in the 1990s; the majority of research since this time 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 majority of the studies reviewed 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. Furthermore, there were no biological data to support an association between magnetic fields and neurodegenerative diseases. The WHO concluded that there were inadequate data to support of an association between magnetic fields and Alzheimer's disease or ALS, stating that "*[w]hen evaluated across all the studies, there is only very limited evidence of*

[13] The replacement article (Li et al., 2020b) is the original article with corrections that are highlighted.

an association between estimated ELF exposure and [Alzheimer's] disease risk" (WHO 2007, p. 194). The most recent SCENIHR report (2015) concluded that newly published studies *"do not provide convincing evidence of an increased risk of neurodegenerative diseases, including dementia, related to ELF MF [magnetic field] exposure"* (SCENIHR, 2015, p. 186).

Recent studies have examined the potential relationship between EMF, electric shocks, and multiple neurodegenerative diseases, including non-vascular dementia, ALS, Parkinson's disease, and Alzheimer's disease (Capozzella et al., 2014; Yu et al., 2014; Brouwer et al., 2015; Fischer et al., 2015; Koeman et al., 2015, 2017; Pedersen et al., 2017; Vinceti et al., 2017; Checkoway et al., 2018; Gunnarsson and Bodin, 2018, 2019; Huss et al., 2018b; Jalilian et al., 2018; Röösli and Jalilian, 2018; Gervasi et al., 2019; Peters et al., 2019, Chen et al., 2021; Filippini et al., 2020; Huang et al., 2020). Many of these studies included methodological improvements (e.g., increased sample size, improved exposure assessment) compared to previous studies. In spite of these improvements, however, the overall evidence from these studies provided no consistent or convincing support for a causal association between ELF EMF exposure and neurodegenerative diseases. Several studies examined the potential role of electric shocks in occupational environments as a possible explanation for the weak and inconsistent association between ELF EMF and ALS; these studies presented no convincing evidence for an association (Das et al., 2012; Grell et al., 2012; van der Mark et al., 2014; Fischer et al., 2015; Vergara et al., 2015; Peters et al., 2019; Chen et al., 2021).

Jalilian et al. (2021) conducted a meta-analysis of occupational exposure to ELF magnetic fields and electric shocks and development of ALS including studies from Europe, the United States, and New Zealand. A weak statistically significant association was reported between magnetic-field exposure and ALS, but the authors noted that due to study heterogeneity and indications of publication bias, "*the results should be interpreted with caution*" (Jalilian et al., 2021, p. 1). No association was observed between electric shocks and ALS. Filippini et al. (2021) conducted a meta-analysis to assess the relationship between ALS and residential exposure to magnetic fields assessed by either distance from overhead power lines or magnetic-field modelling. They reported a decrease in risk of ALS in the highest exposure categories for both distance-based and modeling-based exposure estimates. The authors also reported that their dose-response analyses

"*showed little association between distance from power lines and ALS*" (Filippini et al., 2021, p.1) The authors noted that their study was limited by small sample size, the potential for residual confounding, and by "*some publication bias.*" Huang et al. (2020) conducted a meta-analysis to investigate potential occupational risk factors for dementia or mild cognitive impairment. Positive associations were reported between dementia and work-related magnetic-field exposure; the authors, however, provided no information on the occupations held by the study participants, their magnetic-field exposure levels, or how magnetic-field levels were assessed. This analysis adds little to the weight of the evidence for an association between dementia and magnetic fields, due to its limitations.

In summary, the overall evidence from recent studies provides no consistent or convincing support for a causal association between EMF exposure and neurodegenerative diseases and is consistent with the previous reviews conducted by WHO and SCENIHR.

Cardiovascular Disease

An early hypothesis asserted that magnetic-field exposure may reduce heart rate variability, which in turn is a hypothesized risk for acute myocardial infarction (AMI). In a large cohort of utility workers, Savitz et al. (1999) reported an association with arrhythmia-related deaths and deaths due to AMI among workers with higher magnetic-field exposure. Subsequent studies of similar design did not report a statistically significant increase in cardiovascular disease mortality or incidence of AMI related to occupational magnetic-field exposure, and the WHO concluded that "*[o]verall, the evidence does not support an association between ELF exposure and cardiovascular disease*" (WHO, 2007, p. 220).

The conclusion that there is no support for an association between magnetic fields and cardiovascular diseases has not changed. Elmas (2016) summarized some of the existing literature examining the effects of both long-term and short-term EMF exposure on the heart. The author concluded that "*despite these studies, the effects of EMFs on the heart remain unclear*" and that there is "*not yet any consensus in these works about possible mechanisms by which effects of EMF exposure may occur*" (Elmas, 2016, p. 80).

Standards and Guidelines

The only confirmed effects of exposure to EMF are acute or short-term effects (such as nerve and muscle stimulation) that can occur at very high field levels.[14] Several scientific organizations have published guidelines for exposure to ELF EMF based on these acute health effects. These organizations completed a thorough review of the health research to identify the lowest exposure level below which no health hazards have been found (i.e., a threshold). Exposure limits are then set well below the threshold level to account for any individual variability or sensitivities that may exist.

There are no recommendations, guidelines, or standards in the state of Massachusetts to regulate EMF or to reduce public exposures.[15] ICNIRP reviewed the epidemiologic and experimental research and concluded that there was insufficient evidence to warrant the development of standards or guidelines on the basis of hypothesized long-term adverse health effects such as cancer; rather, the guidelines put forth in their 2010 document set limits to protect against known acute health effects. ICNIRP recommends a screening value for exposure to magnetic fields of 2,000 mG for the public and 10,000 mG for occupational environments (ICNIRP, 2010). The IEEE's International Committee on Electromagnetic Safety (ICES) also recommends limiting magnetic-field exposures at high levels because of the risk of acute effects, although their guidelines are higher than ICNIRP's guidelines; ICES recommends an exposure limit of 9,040 mG for the public and an occupational exposure limit of 27,100 mG (ICES, 2019, 2020). All guidelines incorporate large safety factors. Exposures of any duration below these guidelines are compliant with the basic restrictions (biological limits) of these organization on internal fields in the body. The WHO has deemed adherence to these standards to be protective of public health (WHO, 2006).

[14] These acute and shock-like effects generally cause no long-term damage or health consequences. Limits for the general public and workplace have been set to prevent these effects.

[15] In a 1985 decision, the Massachusetts Energy Facilities Siting Board (EFSB) approved an edge-of-ROW level of 85 mG as a benchmark for comparing different design alternatives. Since then this benchmark has not served as a generally applicable standard or guideline. Instead, the EFSB assesses electric- and magnetic-field levels from transmission lines on a case-by-case basis with a focus on practical, low-cost options to reduce magnetic fields along transmission line rights-of-way. This approach is consistent with recommendations of the WHO (2007) for addressing ELF EMF.

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Appendix A

Author Biographies

Pamela J. Dopart, Ph.D., CIH

Dr. Dopart is an environmental and occupational health scientist who specializes in exposure assessment methods to inform health risk assessments and epidemiologic studies. Her work includes assessing exposures to electromagnetic fields, including power-frequency EMF, in relation to potential biologic and health effects and in communicating the research on EMF and health to the public. Dr. Dopart was awarded her Ph.D. in Environmental Health Sciences by The Johns Hopkins Bloomberg School of Public Health and her Masters in Public Health from the University of Michigan. Prior to joining Exponent, Dr. Dopart was at the National Cancer Institute, during which her research focused on improving methods for assessing occupational and environmental exposures for epidemiologic studies of cancer. She is a member of the Institute of Electrical and Electronics Engineers (IEEE) International Committee on Electromagnetic Safety and the American Industrial Hygiene Association (AIHA).

William H. Bailey, Ph.D.

Dr. William H. Bailey is a Principal Scientist in Exponent's Health Sciences practice. Dr. Bailey specializes in applying state-of-the-art assessment methods to environmental and occupational health issues. His 30 years of training and experience include laboratory and epidemiologic research, health risk assessment, and comprehensive exposure analysis. Dr. Bailey has investigated exposures to alternating current, direct current, and radiofrequency electromagnetic fields, 'stray voltage,' and electrical shock, as well as to a variety of chemical agents and air pollutants. He is particularly well known for his research on potential health and environmental effects of electromagnetic fields and has served as an advisor to numerous state, federal, and international agencies. He was invited to address the potential environmental effects of electromagnetic fields from submarine cables at the Long Island Sound Bottomlands Symposium: Study of Benthic Habitats, sponsored by the Connecticut Academy of Science and Engineering, led Exponent teams in assessments of EMF from submarine cables for BOEM reports in 2011 and 2019, and has performed exposure and marine impact assessments of EMF for multiple AC and DC submarine cable projects, including offshore wind farms in the US and Canada.