Biological effects of non-ionizing electromagnetic energy: A critical review of the reports by the US National Research Council and the US National Institute of Environmental Health Sciences as they relate to the broad realm of EMF bioeffects

Magda Havas

Abstract: Our dependence on electricity and our growing dependence on wireless telecommunication technology is causing this planet to be inundated with electromagnetic energy ranging in frequency from less than 60 Hz to greater than 2 GHz. Concerns expressed by the public, who live near power lines, cell phone antennas, or television and radio broadcast towers, have prompted two major reviews: one by the US National Research Council (NRC) and the other by the US National Institute of Environmental Health Science (NIEHS). Both of these documents deal with the biological and health effects primarily in a residential setting of extremely low frequency (ELF) or power frequency (50 and 60 Hz) fields. This paper critically evaluates the NRC and NIEHS documents. This evaluation includes both the content and the process leading to the final reports. It summarizes the information available on human exposure to electric and magnetic fields and identifies key biological markers and potential mechanisms that have been linked to electromagnetic exposure. It examines the conclusions of both documents in terms of the slightly broader realm associated with occupational exposure, non-power frequency fields, EMF hypersensitivity, and response of species other than humans. It presents some of the scientific controversy surrounding the question "Are low frequency electric and magnetic fields harmful?" and examines the concepts of bias and consistency in data interpretation. This paper also attempts to place the discussions about technologically generated fields (technofields) into a much broader perspective, a perspective that includes naturally occurring geofields and biofields.

Key words: leukemia, breast cancer, melatonin, calcium flux, extremely low frequency electromagnetic fields, radio frequency radiation.

Résumé : Notre dépendance de l'électricité et notre dépendance croissante des technologies de communication sans fils conduisent à une inondation de la planète par l'énergie électromagnétique, de fréquences de moins de 60 Hz à plus de 2 GHz. Les préoccupations des

Received June 28, 1999. Accepted March 13, 2000. Published on the NRC Research Press web site on October 11, 2000.

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gens qui vivent à proximité des lignes de transport d'électricité, des antennes de téléphones cellulaires, ou des tours d'émission de radio et de télévision, ont provoqué la mise sur pied de deux programme d'évaluation de leurs effets, aux Etats-Unis : le premier par le Conseil national de recherches (NRC), et le second par l'Institut national des sciences de l'environnement et de la santé (NIEHS). Les deux rapports traitent des effets sur la biologie et la santé, surtout dans des environnements résidentiels exposés à des fréquences extrêment basses (ELF) ou à des champs de fréquences énergétiques (50 et 60 Hz). L'auteur présente une revue critique des rapports des NRC et NIEHS américains. Cette évalution fait état des contenus ainsi que des processus qui ont conduit à ces rapports finaux. On résume l'information disponible sur l'exposition des humains aux champs électriques et magnétiques, et on identifie des marqueurs biologiques clés et des mécanismes possibles qui ont été reliés à l'exposition aux ondes électromagnétiques. On examine les conclusions des deux rapports en termes d'une réalité un peu plus large associée aux expositions occupationnelles, aux champs de fréquences non-énergétiques, à l'hypersensibilité aux EMF, et à la réaction de d'autres espèces que les humains. On fait état de quelques controverses scientifiques entourant la question « Les basses fréquences électriques et les champs magnétiques sont-ils nuisibles? » et on examine les concepts de biais et de congruence dans l'interprétation des données. Cette revue tente également de situer la discussion sur les champs technologiquement générés (technofields) dans une perspective beaucoup plus large incluant les champs géologiques (geofields) et les champs biologiques (biofields) d'origine naturelle.

Mots clés : leucémie, cancer du sein, mélatonine, flux calcique, champs électromagnétiques à fréquences extrêment basses, radiation des radio fréquences.

[Traduit par la Rédaction]

1. Introduction

The biological effects of low frequency electric and magnetic fields (EMF) have become a topic of considerable scientific scrutiny during the past two decades. The flurry of research in this area has contributed greatly to our understanding of the complex electromagnetic environment to which we are exposed but it has not resolved the controversy over whether the effects are harmful. If anything it has polarized into two camps the small group of scientists concerned with health effects: those who think exposure to low frequency electromagnetic fields causes adverse health effects and those who do not. Those who believe there is a causal association are trying to find the mechanisms responsible and those who question the concept of causality think this research is a waste of time and money. In contrast, the majority of scientists in this field are concerned with the science and not health effects, and they recognize that the data show there are effects that are of interested from the standpoint of basic research.

Controversy is the norm when complex environmental issues with substantial economic and health consequences are scientifically scrutinized. Asbestos, lead, acid rain, tobacco smoke, DDT, PCBs (and more recently estrogen mimics) were all contentious issues and were debated for decades in scientific publications and in the popular press before their health effects and the mechanisms responsible were understood. In some cases the debate was scientifically legitimate while in others interested parties deliberately confused the issue to delay legislation (Havas et al. 1984).

The public, uncomfortable with scientific controversy and unable to determine the legitimacy of a scientific debate, wants a clear answer to the question, "Are low frequency electric and magnetic fields harmful?"

As a direct response to public concern two major reports have been published recently on the health effects of low frequency electric and magnetic fields. The first, published in 1997 and entitled *Possible Health Effects of Exposure to Residential Electric and Magnetic Fields,* was conducted by an Expert Committee of the US National Research Council. The second, *Assessment of Health Effects from Exposure to Power-Line Frequency Electric and Magnetic Fields,* published 1 year later, was a Working Group Report of the US National Institute of Environment Health Sciences.

These reports attempt to make sense of the many (and what sometimes appears to be contradictory)

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results from different fields of study, related to the health effects of power-line frequency fields. They can be considered state of the art reports on health effects of low frequency (50 and 60 Hz) electric and magnetic fields and are likely to be highly influential documents. For this reason, it makes sense to start a review on the biological effects of electromagnetic fields with these two reports.

Henceforth, the two documents, cited below, will be referred to as the NRC and NIEHS Reports.

National Research Council (US) Committee on the Possible Effects of Electromagnetic Fields on Biologic Systems. 1997. *Possible Health Effects of Exposure to Residential Electric and Magnetic Fields*, National Academy Press, Washington, D.C., 356 pp.

Portier, C.J., and Wolfe, M.S. (*Editors*). 1998*c*. *Assessment of Health Effects from Exposure to Power-Line Frequency Electric and Magnetic Fields*. National Institute of Environmental Health Sciences Working Group Report of the National Institutes of Health. NIH Publication No. 98-3981, Research Triangle Park, N.C., 508 pp.[1]

However, these documents, instead of illuminating the biological effects of electromagnetic fields, cast a spotlight only on a small part of the electromagnetic spectrum and only on a portion of the EMF debate, and for that reason they need to be placed in perspective. So, while this review will begin with the NRC and NIEHS documents it will not end with them.

The purpose of the present paper is 4-fold:

(1) to evaluate the NRC and NIEHS documents including the content and the process leading to the final report

(2) to characterize human exposure to electric and magnetic fields

(3) to identify key biological markers and mechanisms that have been linked to EMF exposure and to assess the degree of confidence associated with each

(4) to examine the conclusions of both reports in terms of the slightly broader area of biological effects associated with

  (*i*) occupational exposure rather than just residential exposure
  (*ii*) frequencies other than those associated with power distribution (from static fields to those generated by wireless communication technology in the microwave region of the electromagnetic spectrum)
  (*iii*) hypersensitivity to electromagnetic energy
  (*iv*) response of species other than humans

The question "Are low frequency electric and magnetic fields harmful?" is valid and timely. The answer is likely to have far reaching consequences, considering our growing dependency on electric power, computer technology, and wireless telecommunication, and is likely to be of interest to a large population using, manufacturing, selling, and regulating this technology.

2. Background information

In the broadest sense, research involving electromagnetic energy can be classified into three categories based on the source of that energy. Public concern is focused on electromagnetic fields generated by our technology, which I call *technofields*. These include radiation and fields produced by power

[1] On December 3, 1998, the Department of Health and Human Services sent out an Erratum for the EMF Working Group Report. Those corrections are included in this review.

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distribution networks, by computers and microwave ovens, by cell phones and wireless communication towers, and by satellite communication systems worldwide.

In addition to these technofields, all living organisms are also exposed to naturally produced electromagnetic fields/radiation generated by the earth, the sun, and the rest of the cosmos, which I call *geofields*. Geofields are naturally occurring abiotic fields that have components that are unpredictable in their fluctuations (solar eruptions), cyclic (diurnal, seasonal), and relatively stable (earth's magnetic field).

The third field is generated by all living organisms during any form of metabolic activity, which I call *biofields*. Most of the research has focused on either electric or magnetic fields generated by the heart, brain, and nerve cells. Biofields tend to be much weaker than either geofields or technofields but can be measured and have been used to monitor metabolic activity and to diagnose ill health. Some even claim that these biological energies can be used to restore energy imbalance and to heal (therapeutic touch, reiki, acupressure). Biofields have been recognized since ancient times and have been called, among other things, subtle energy, acupuncture points and meridians, prana, aura, chi, and chakras.

These three sources of electromagnetic energy, depicted as three overlapping Venn diagrams in Fig. 1, interact and it is these interactions that most interest us. Solar flares may be sufficiently powerful to knock out satellites or to disrupt power distribution, as happened on March 13, 1989, during a particularly powerful solar storm when the province of Quebec was plunged into darkness (Kappenman 1996). The ionosphere reflects certain electromagnetic frequencies, much like a mirror reflects light, and enables short-wave radio communication across the globe. Both of these are examples of geofield and technofield interactions. The interactions in Fig. 1 are not intended to be all inclusive but rather to provide a broad range of potential field interactions, a number of which have yet to be scientifically investigated.

The areas of current debate are the interactions between living organisms and technologically generated fields at power line frequencies (60 Hz in North America and 50 Hz elsewhere) and at frequencies generated by computers, cell phones, etc., in the kilo (10^3), mega (10^6), and giga (10^9) hertz range (Fig. 2).

Until recently, frequencies below the microwave band were assumed to be "biologically safe." This began to change in the 1960s and early 1970s when the Soviet Union reported health effects experienced by their high voltage switchyard workers (Korobkova et al. 1972).

Within several months of the first 500 kV substation becoming operable in the Soviet Union, maintenance workers complained of headaches, reduce sexual potency, and general ill health. The electric field was assumed to be responsible for the health complaints. Personnel working with 500 and 750 kV lines were compared with workers at 110 and 220 kV substations. Maximum intensities within the 500 and 750 kV switchyard were generally between 15 and 25 kV/m and biological effects were reported above 5 kV/m. The report states that a current of "80–120 μA flowing through a man for a long time affects him unfavorably." No specific details are presented. The document recommends methods of screening and provides a time limit for daily exposure as follows: unlimited exposure at 5 kV/m, 180 min at 10 kV/m, 90 min at 15 kV/m, 10 min at 20 kV/m, and 5 min at 25 kV/m. This document, one of a series on the effects of 500 and 750 kV substations on workers, received little attention in the West. It took another decade for the West to document the harmful effects of high voltage power lines on substation workers and their families (Nordstrom et al. 1983; Nordenson et al. 1984). These documents are presented later in this report.

It was not until Nancy Wertheimer and her colleague, Ed Leeper, reported an increased incidence of childhood leukemia, lymphoma, and nervous system tumors associated with residential exposure to power line frequency fields in Denver, Colorado, that the West began to take notice (Wertheimer and Leeper 1979). Paul Brodeur did much to publicized this type of information in *The New York Times* and elsewhere (see Brodeur 1993), alerting the public and enraging members of the scientific community who were unwilling to accept the Wertheimer and Leeper results.

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Fig. 1. Examples of interactions of electromagnetic fields generated by geofields (G), biofields (B), and technofields (T).

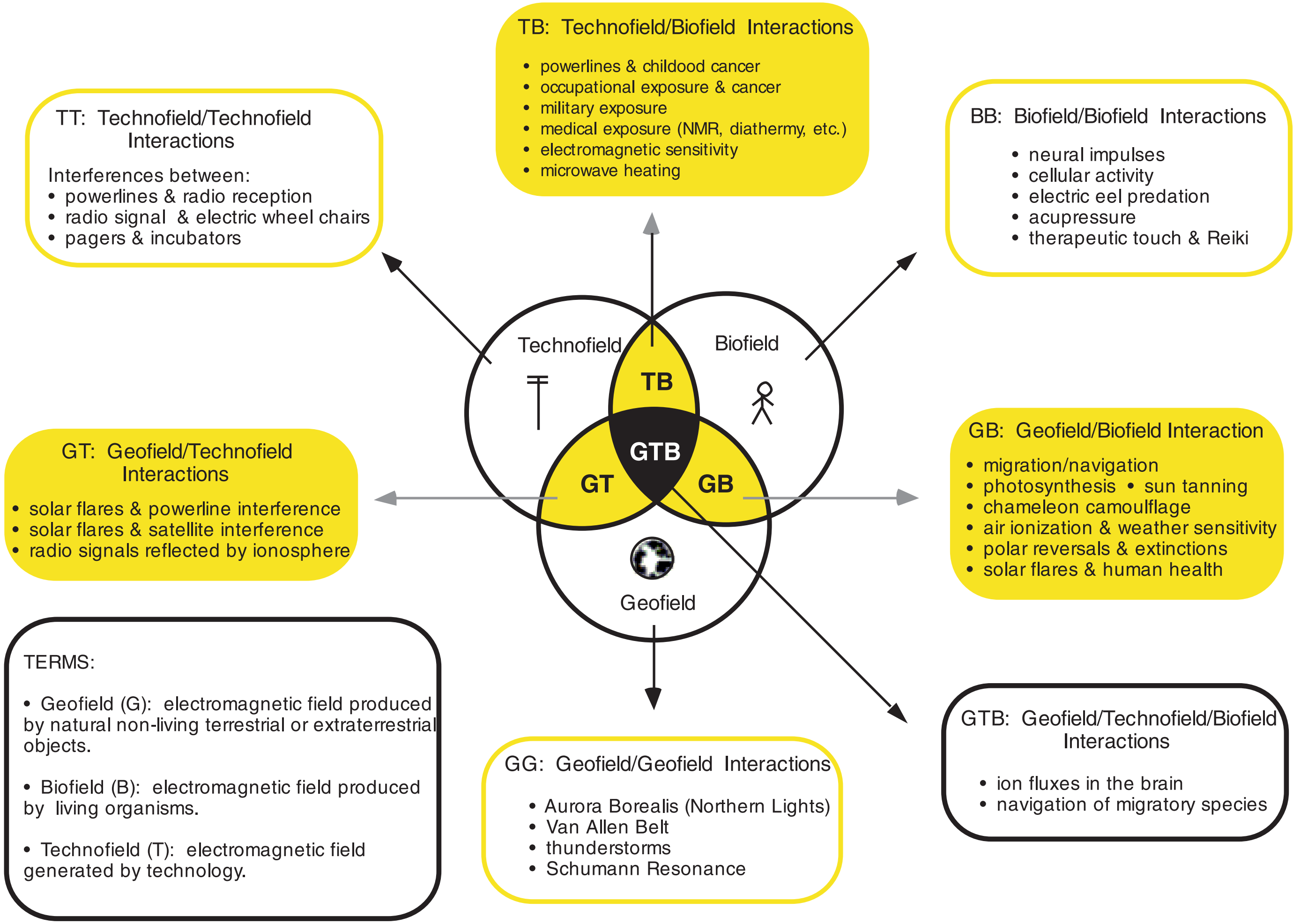

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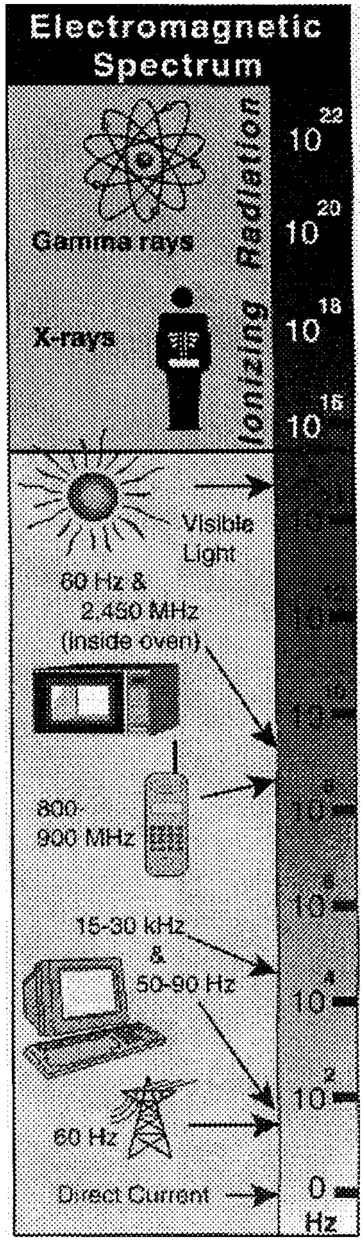
Fig. 2. Electromagnetic spectrum showing frequencies from ionizing radiation to direct current. Selected technologies and the frequencies at which they operate are shown. (Reprinted with permission from EMF Rapid 1996, *Questions and answers: EMF in the workplace*.)



The Wertheimer and Leeper study was repeated in various locations, and by the early 1990s more than a dozen studies were published on childhood cancer. While some studies found no effects (Fulton et al. 1980; Verkasalo et al. 1993, 1994; Tynes and Haldersen 1997), others confirmed the Wertheimer and Leeper results (NRPB 1992; Ahlbom et al. 1993; Washburn et al. 1994; Feychting et al. 1995; Meinert and Michaelis 1996; Linet et al. 1997; Michaelis et al. 1998).

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Studies of childhood cancers were followed by studies of adult cancers in occupational as well as residential settings and by effects of electromagnetic fields on reproduction. Residential exposure was associated with miscarriages (Wertheimer and Leeper 1986, 1989) while occupational exposure was linked to various reproductive problems as well as adult cancers, including primary brain tumors, leukemias, and breast cancer among both men and women (Lin et al. 1985; Goldhaber et al. 1988; Demers et al. 1991; Matanoski et al. 1991; Floderus et al. 1993; Floderus et al. 1994; London et al. 1994; Loomis et al. 1994; Cantor et al. 1995; Savitz and Loomis 1995; Coogan et al. 1996; Miller et al. 1996; Feychting et al. 1997; Kheifet et al. 1997). Members of the scientific community, seeing similarities between childhood and adult cancers, became greatly concerned.

One major problem with the epidemiological studies was that information on exposure was scarce. Wire codes were used to provide a surrogate metric for the magnetic field. Once portable gauss meters sensitive to power line frequencies became available, the spot measurement and 24-h monitoring supplemented the wire codes. Of these three methods, the wire codes are highly associated (as measured by odds ratios or relative risk) and the spot measurements are poorly associated with magnetic field exposure and health effects in epidemiological studies (London et al. 1991; Feychting and Ahbol 1993; Savitz et al. 1988). The odds ratio (OR) and relative risk (RR) are two metrics epidemiologists use to compare a test population (observed) with a control population (expected) for a specific endpoint (cancer, for example). The higher the OR (ratio of observed to expected), the greater the association between an agent and an end point.

In the past decade appliances, rooms, and houses have been monitored and we have a much better understanding of the magnetic flux density to which we are exposed (EPA 1992; EPRI 1993 as cited in NRC 1997). Whether magnetic flux density is the only biologically important metric or, indeed, the one we should be measuring remains to be determined.

The epidemiological studies were complemented by in vivo and in vitro studies that explored the mechanisms responsible for the biological effects of electromagnetic fields. Because of the novelty of this type of research there were (and still are) no standardized protocols for testing. In the literature experimental intensities for magnetic flux density range from less than 0.1 μT to greater than 300 mT;[2] daily exposure varies from 30 min to 24 h; and duration of exposure extends from days to years (Ekstrom et al. 1998; Beniashvili et al. 1991; Loscher et al. 1994; Mevissen et al. 1996, 1998*a,b*; NTP 1998). Some of the tests involve continuous, homogeneous fields, others involve gradients, and still others use intermittent fields (pulsed or digital) with on:off cycles ranging from seconds to hours. Interpreting such a wide array of exposure conditions is not an easy task. With an understanding of all of these difficulties, the NRC and the NIEHS committees examined the literature. What follows is a review of these two documents: the mandate, the process, and the conclusions.

3. Process used by the National Research Council and the National Institute of Environmental Health Science

3.1. Mandate

The NRC and NIEHS were charged by Congress to review the scientific literature and to assess the biological effects of exposure to low frequency electromagnetic fields. Although these reports were independent of each other, several members served on both committees and both committees liaised with the US Department of Energy.

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[2] The strength of the magnetic field, technically referred to as “magnetic flux density” and represented by the symbol “*B*” is measured in units of tesla (T) in the preferred SI system and in units of gauss (G) in the cgs system. One T is equal to 10 000 G. To place these units into perspective, the earth’s “average” magnetic field is about 50 μT (500 mG); fields under power lines are in the order of 1 μT (10 mG), fields associated with childhood cancers are above 0.2 μT (2 mG), and the fields generated by living cells are considerably less than 0.001 μT (0.01 mG).

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National Research Council mandate

The specific mandate placed before the NRC Expert Committee is the following (NRC 1997, p. 1):

(1) To review and evaluate the existing scientific information on the possible effects of exposure to electric and magnetic fields on the incidence of cancer, on reproduction and developmental abnormalities, and on neurobiologic response as reflected in learning and behavior;

(2) To focus on exposure modalities found in residential settings; and

(3) To identify future research needs and to carry out a risk assessment insofar as the research data justified this procedure.

National Institute of Environmental Health Science mandate

The National Institute of Environmental Health Sciences (NIEHS) was charged by Congress *to prepare and submit an evaluation of the potential human health effects from exposure to extremely low frequency electric and magnetic fields (ELF EMF)* (NIEHS Report 1998, p. iii). In addition to their "evaluation" (which is the NIEHS Report, 1998), NIEHS funded research to address key questions (some of those are presented in their final report) and sponsored three science symposia.

Comparison of the National Research Council and National Institute of Environmental Health Science mandates

Both Committees focus on low frequency electric and magnetic fields (those associated with power distribution at 50 and 60 Hz). Consequences of exposure to ionizing radiation, ultraviolet, visible, infrared, microwave, and radio frequencies are not included in either report, except in a cursory fashion.

The mandate of the NRC Committee is much more restricted in its scope than that of the NIEHS Committee. Occupational exposure is not part of the NRC Committee mandate, hence its brief, but significant, discussion in the document does not appear anywhere in the Executive Summary. Other sources of exposure within the home (appliances, for example) and outside the home (transportation) are discussed in a much more cursory fashion in the NRC document than in the NIEHS document.

A narrow focus on power line frequencies in both reports (with insufficient assessment of higher frequencies associated with cell phones, for example) and an absence of occupational exposure and electromagnetic sensitivities in the NRC mandate are the key weaknesses.

Although not part of their mandate, both documents provide excellent summaries of the physics of electric and magnetic fields; of exposure assessment; and of the advantages and limitations of in vitro, in vivo, and epidemiological studies. They also summarize the bioeffects of electromagnetic fields as studied in genotoxicology, neuroendocrinology, cellular communication/replication, and biophysics.

3.2. Participants and the selection process

Contributors to the National Research Council document

The Expert Committee, convened by the National Research Council (NRC), consisted of 16 members, 9 with previous experience on the biological effects of EMFs and 7 new to this area but with related expertise. No details are given about the selection criteria used. Four of the members served on both the NRC and the NIEHS Committees, as indicated in Table 1.

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Table 1. Members of the NRC Committee on the *Possible Health Effects of Exposure to Residential Electric and Magnetic Fields*; primary affiliation and areas of expertise (NRC 1997).

Name	Affiliation	Position and expertise	Number cited[a] NRC	Number cited[a] NIEHS
Charles F. Stevens (Chair)	Howard Hughes Medical Institute, Salt Institute, La Jolla, Calif.	Professor, neurobiology	0	0
David A. Savitz (Vice-Chair)	Department of Epidemiology, University of North Carolina, Chapel Hill, N.C.	Professor, epidemiology, cancer and reproduction	9	9
Larry E. Anderson[b]	Pacific Northwest National Laboratory, Richland, Wash.	Staff Scientist, neurochemistry	0	1
Daniel A. Driscoll	Department of Public Service, State of New York, Albany, N.Y.	Professional Engineer, electrical and biomedical	0	0
Fred H. Gage	Laboratory of Genetics, Salt Institute, San Diego, Calif.	Professor, central nervous system disorders	0	0
Richard L. Garwin	IBM Research Division, T.J. Watson Research Division, Yorktown Heights, N.Y.	Fellow Emeritus, nuclear physics	0	0
Lynn W. Jelinski	Center for Advanced Technology-Biotechnology, Cornell University, Ithaca, N.Y.	Professor, nuclear magnetic resonance	0	0
Bruce J. Kelman	Health and Environmental Sciences, Golder Associates, Inc., Redmond, Wash.	National Directory, reproductive and developmental toxicology	0	0
Richard A. Luben[b]	Department of Biomedical Sciences, University of California at Riverside, Riverside, Calif.	Associate Professor, cellular and molecular biology	4	2
Russel J. Reiter	Department of Cellular and Structural Biology, University of Texas Health Sciences Center, San Antonio, Tex.	Professor, neuroendocrinology, brain chemistry, reproductive and behavioral biology	9	3
Paul Slovic	Decision Research, Eugene, Oregon, and Department of Psychology, University of Oregon	President and Professor, risk analysis	1	0
Jan A.J. Stolwijk	Department of Epidemiology and Public Health, Yale University, School of Medicine, New Haven, N.C.	Professor, epidemiology	0	0
Maria A. Stuchly	Department of Electrical and Computer Engineering, University of Victoria, Victoria, B.C.	Professor, numerical and experimental modeling	5	4

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Table 1. (*concluded*).

Name	Affiliation	Position and expertise	Number cited[a] NRC	NIEHS
Daniel Wartenberg[b]	Department of Environmental and Community Medicine, UMDNJ-Robert Wood Johnson, Medical School, Piscataway, N.J.	Associate Professor, epidemiology	2	1
John S. Waugh	Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Mass.	Professor, nuclear magnetic resonance	0	0
Jerry R. Williams[b]	The John Hopkins Oncology Center, Baltimore, Md.	Professor, oncology	0	0

[a]Number of first-authored papers cited in the NRC and NIEHS Reports.
[b]Served as member on both NRC and NIEHS Committees.

The following individuals presented papers at a workshop to aid the Expert Committee: Anders Ahlbom (Karolinska Institute), Edward P. Washburn (DOE), Keith Florig (Resources for the Future), Joseph V. Brady (John Hopkins University), Robert L. Brent (Dupont Institute and the Jefferson Medical College), Gary S. Stein (University of Massachusetts), James Weaver (MIT), Ken McLeod, who also served as a member of the NIEHS Committee (State University of New York at Stonybrook), and Robert Tardiff (E.A. Engineering Sciences and Technology, Inc.). Jay Lubin (National Cancer Institute), John Tukey (Princeton University), and William Feero (Electric Research and Management Inc.) provided statistical evaluation and exposure assessment.

Contributors to the National Institute of Environmental Health Science document

Members of the NIEHS Working Group were “selected carefully after screening by the NIEHS and discussions with its two standing external advisory boards,” the National EMF Advisory Committee and the EMF Interagency Committee (NIEHS, p. 8). No information on the specific selection criteria is provided.

National Institute of Environmental Health Science organized a 30-member Working Group (Table 2) who, in turn, did a comprehensive review of the data that included a review of more than 830 references. They attended three science symposia and participated at a working group meeting held at Brooklyn Park, Minnesota, 16–24 June 1998, during which time they wrote their report. The report was later reviewed and edited for clarity by a science writer, E. Heseltine, an Associate Professor at Université Lumiere. This 9-day report took 7 person-years of effort of which 4 person-years were attributed to the summaries of the three science symposia.

Additional contributions were made by G.M. Blumenthal (NIEHS) and J.E. Morris (Battelle, Pacific Northwest National Laboratories), who helped write the first draft, nine staff from the NIEHS, two Technical Training specialists from OAO Corporation, Diana Phillips (personal Communication Services Inc.), S.D. Linde (National EMF Advisory Committee), and Imre Gyuk (US DOE).

There were also 18 “Observers,” 2 listed as “private citizens” and the rest affiliated with either private enterprise, government, or research and publication groups. These affiliations include the Federal Energy Regulatory Commission, US EPA, Office of Naval Research, IEEE-EMF Society, EMF Health and Safety Digest, National Electrical Manufacturers Association, Minnesota Power, Northern States Power Co., Inc., Research Institute of Electric Power, Edison Electric Institute, Caring Technologies, Inc., Central United Illuminating, Watson & Renner, and Robert S. Banks Associates.

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Table 2. Members of the NIEHS Working Group on the *Assessment of Health Effects from Exposure to Power-Line Frequency Electric and Magnetic Fields* (NIEHS 1998).

			Number cited[a]	
Name	Affiliation	Position	NIEHS	NRC
M.A. Gallo (Chair)	Department of Environmental and Community Medicine, UMDNJ-Robert Wood Johnson Medical School, Piscataway, N.J.	Director and Professor	0	0
A.L. Brown (Vice-Chair)	Department of Pathology and Laboratory Medicine, University of Wisconsin at Madison, Madison, Wisc.	Professor	0	0
C.J. Portier (Meeting Coordinator)	Laboratory of Computational Biology & Risk Analysis and EMF Hazard Evaluation, NIEHS, Research Triangle Park, N.C.	Chief and Coordinator	3	0
L.E. Anderson[b]	Battelle, Pacific Northwest National Laboratories, Richland, Wash.	Research Scientist	1	0
J.D. Bowman	National Institute for Occupation Safety and Health, Taft Laboratories, Cincinnati, Ohio	Research Industrial Hygienist	5	0
E. Cardis[c]	Unit of Radiation and Cancer, International Agency for Research on Cancer, Lyon Cedex, France	Chief	0	0
F.M. Dietrich	Electric Research and Management, Inc., Pittsburgh, Pa.	Principal Engineer	0	0
M.L. Dubocovich	Department of Molecular Pharmacology and Biological Chemistry, Northwestern University Medical School, Chicago, Ill.	Professor	1	0
J.S. Felton[c]	Molecular and Structural Biology Division, University of California, Livermore, Calif.	Division Leader	0	0
M. Feychting	Institute of Environmental Medicine, Karolinska Institute, Stockholm, Sweden	Epidemiologist	8	2
P.C. Gailey	Electric and Magnetic Fields Bioeffects Research Program, Oak Ridge National Laboratory, Oak Ridge, Tenn.	Director	1	0
C. Graham	Department of Life Sciences, Midwest Research Institute, Kansas City, Mo.	Senior Advisor	0	0
G.J. Harry	Laboratory of Toxicology, National Institute of Environmental Health Sciences, Research Triangle Park, N.C.	Group Leader (neurotoxicology)	0	0
L.I. Kheifets	EPRI, Stanford, Los Altos Hills, Calif.	Senior Scientist	4	0
R.A. Luben[b]	Department of Biomedical Sciences, University of California at Riverside, Riverside, Calif.	Associate Dean of Research	2	4

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Table 2. (*concluded*).

Name	Affiliation	Position	Number cited[a] NIEHS	NRC
M-O. Mattsson	Department of Cellular and Developmental Biology, Umea University, Umea, Sweden	Associate Professor	0	0
K.J. McLeod (presentation to NRC Committee)	Department of Orthopedics, State University of New York at Stony Brook, Stony Brook, N.Y.	Associate Professor	9	0
S.C. Miller[b]	Signal Transduction Program, Pharmaceutical Discovery Division, SRI International, Menlo Park, Calif.	Director	2	0
M. Misakian[b]	National Institute of Standards and Technology, Gaithersburg, Md.	Physicist	3	3
C. Polk[b]	Department of Electrical and Computer Engineering, University of Rhode Island, Kingston, R.I.	Professor Emeritus	9	6
W.R. Rogers[c]	Environmental Sciences, Department of Family Practice, School of Public Health, University of Texas, San Antonio, Tex.	Associate Professor	5	1
A. Sastre	Health Assessment and Research Center, Midwest Research Institute, Kansas City, Mo.	Principal Scientist	0	0
C.D. Sherman	Department of Mathematics, San Francisco State University, San Francisco, Calif.	Assistant Professor	0	0
L.E. Slesin	Microwave News, New York, N.Y.	Editor	0	0
R.G. Stevens	Department of Molecular Biosciences, Battele, Pacific Northwest National Laboratory, Richland, Wash.	Staff Scientist	3	1
L. Tomatis	Instituto Per L'Infanzia, Trieste, Italy	Scientific Director	0	0
D. Wartenberg[b]	Department of Environment and Community Medicine, UMDNJ-Robert Wood Johnson Medical School, Piscataway, N.J.	Associate Professor	1	2
J.R. Williams[a,c]	Department of Radiation Oncology, John Hopkins University, Baltimore, Md.	Professor of Oncology	0	0
H. Yamasaki	Unit of Multistage Carcinogenesis, International Agency for Research on Cancer, Lyon Cedex, France	Chief	0	0
M.G. Yost	Department of Environmental Health, University of Washington, Seattle, Wash.	Associate Professor	3	2
P.L. Zweiacker[c]	Environmental Permitting, Texas Utilities Services, Dallas, Tex.	Manager	0	0

[a]Number of first-authored papers cited in the NRC and NIEHS Reports.
[b]Member on both NRC and NIEHS Committees.
[c]Co-author of Minority Report.

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Comparison of the National Research Council and National Institute of Environmental Health Science committee membership

Two key concerns need to be addressed in any group deliberation: expertise and bias. Are individuals able to contribute their expertise about a certain issue; can they weigh the evidence fairly and then come to a conclusion that is devoid of bias or prejudgment?

The first concern, that of expertise, is not an issue. Membership on the committees is diverse and distinguished (Tables 1 and 2). Members cover a broad range of expertise, including epidemiology, cancer research, neuroendocrinology, reproductive and developmental biology, physiology, physics, engineering, and risk assessment. Some key individuals are missing but numbers need to be limited in any selection process.

The second concern, that of bias, was a concern of the founding organizations as well. In the Preface to the NRC Report the following statement is made:

> Data are seldom sufficient to provide a definitive answer to the possible health effects of a physical or chemical agent in the environment. In such cases, professional judgment plays a large role in forming conclusions. It is especially important that the scientists selected for the evaluations be open to the evidence about the issues to be studied, wherever it might lead.

In my opinion there is evidence of bias in several chapters of the NRC Report. However, I am unable to judge, based solely on the written text, the degree to which this is cultural bias, associated with standards used by scientific subdisciplines, or prejudicial bias.

What is clear is a strong disagreement between the epidemiologists and the cell/animal physiologists evident in several chapters but particularly in the one on Risk Assessment. The signal-to-noise ratio for much of the published literature is low and while the epidemiologists hear the signal, the physiologists hear the noise and are thus unable to come to an agreement. If conclusions were based on majority vote (as they were in the NIEHS Report) then the number of committee members in each subdiscipline may be important. The democratic process of voting does not necessarily ensure *truth* in science since the majority can be wrong.

3.3. Source of information

National Research Council references

The NRC document reviewed 520 references published from 1953 to 1996 with the majority of the references published in the 1980s (38 %) and 1990s (51%) (Table 3). A paper had to be published in a peer-reviewed journal for inclusion in this document. Technical reports delivered at scientific meetings provided background information, but were not used to form judgments, with the exception of the US Environmental Protection Agency (EPA) and Electric Power Research Institute (EPRI) publications on exposure data (NRC p. 19).

In forming judgments, the members had more exacting criteria:

> The body of evidence is weighed together to reach an overall assessment of possible hazard. If the results from several areas of research (e.g., epidemiologic studies, tests in cell systems, or whole-animal studies) are consistent and have been replicated, and if a biologically plausible mechanism of action for the effect is evident, the evidence for the effect is given great weight. In contrast, a body of evidence that includes inconsistent and conflicting results, no replication of results, and effects that are often at the threshold of detection might be given little weight in reaching a conclusion (NRC, p. 16).

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Table 3. References cited in the reports by the National Research Council (1997) and the National Institute of Environmental Health Science (1998) according to date of publication.

	NRC 1997		NIEHS 1998[a]		References in common	
Decade of publication	Number	%	Number	%	Number	%
1997 and 1998[b]	0	0	158	19	0	0
1990s	263	51	625	75	113	60
1980s	200	38	162	20	66	35
1970s	46	9	33	4	9	5
1960s	8	1.5	7	0.8	0	0
1950s	2	0.4	1	0.1	1	0.5
1940s	0	0	1	0.1	0	0
TOTAL	519 ± 1	100	829 ± 2	100	189 ± 3	100

[a]One reference without a date.
[b]These references were not available to the NRC Committee. They are included in 1990s counts for the NIEHS Report.

National Institute of Environmental Health Science references

The NIEHS document reviews 830 references published from 1941 to 1998 with the majority of the references (75%) published in the 1990s (Table 3). Only 186 references are common to both the NRC and NIEHS Documents. An additional 158 references published in 1997 and 1998, which the NRC Committee did not have access to, are also included in the NIEHS Document. Two key questions that need to be addressed are (1) Do these new references answer key questions raised in the NRC Report? and (2) Do the data confirm or refute the NRC conclusions?

Although not explicitly stated, the criterion for reference selection appears to be similar to that used by the NRC Committee, namely papers in peer-reviewed journals. Also, three symposia provided background information for the expert committee to consider (Portier and Wolfe 1997, 1998*a*, 1998*b*).

The Committees relied almost exclusively on post 1980 data and ignored some excellent research conducted in the 1960s and 1970s. Several key studies by pioneers (Adey, Becker, Frey, and Marino, to name a few) were not considered, and neither was the work done in the former Soviet Union and in Eastern European countries despite English translations (Presman 1970; Dubrov 1978; Kulczycki 1989). Literature that might provide a broader perspective, biological responses to geomagnetic and geoelectric fields, was also not considered (Tromp 1974; Sulman 1980; Kirschvink et al. 1985).

If the fundamental question is, “Do low frequency electromagnetic fields affect living systems,” then these two reports are incomplete. They focus on a narrow band of the electromagnetic spectrum (power frequencies). They consider EMFs generated by our technology (technofields) but not those naturally generated by natural processes (geofields and biofields). They focus entirely on response of humans and ignore other species. Even the in vivo studies with rats and mice and the in vitro studies with cell suspensions are designed to help us better understand the mechanisms as they pertain to humans. They examine the potentially harmful effects and ignore beneficial therapeutic uses (except for healing of bone fractures). To properly answer the question raised above, a much broader perspective is needed, but this was outside their mandate.

3.4. Decision making process

National Research Council decision making

The NRC document provides little information on the decision making process. The Chair states that the report took nearly 3 years of committee study and numerous hours of committee deliberations,

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which "we spent assessing and evaluating the data and synthesizing our conclusions based on the data."

National Institute of Environmental Health Science decision making

The NIEHS conducted research on the carcinogenicity in experimental animals and improved methods of measuring exposure. NIEHS also enacted a two-tiered process for collecting and evaluating information for the final report.

As the first part of this process, three Science Review Symposia were held. The symposia were open to the public and were designed to encourage debate. The first was in Durham, North Carolina, in March 1997. Participants were asked to address specific questions concerning the mechanisms governing the interactions of ELF EMF with biological systems in vitro and using biophysical theories. The second symposium was on the epidemiology of exposure to ELF EMF held in San Antonio, Texas, in January 1998, and the third on in vivo clinical investigations held in Phoenix, Arizona, April 1998. The discussions of these symposia have been edited by Portier and Wolfe (1997, 1998*a*, 1998*b*).

As the second part of this process a Working Group was selected (as previously discussed) to conduct "... a rigorous, multi-disciplinary, scientific assessment of available data on the health effects of EMF ... The Process was publicly open, scholarly, objective, and sufficiently flexible to accommodate the changing face of EMF research and public health concerns." (NIEHS 1998, p. 8). At a 9-day working session in Brooklyn Park, Minnesota, members prepared the final NIEHS document. Working in subgroups on a draft prepared in advance of the meeting, members read, modified, and rewrote the drafts to reflect Group consensus.

The evaluations of carcinogenicity (and other health end-points) were reached following the guidelines used in the International Agency for Research on Cancer (IARC) *Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Humans* with minor modifications as presented in their Appendix.

For each critical statement dealing with the biological effect of electric and magnetic fields, members voted and the votes were recorded. One member of the Working Group was unable to continue serving, hence 29 individuals were eligible to vote. The votes are summarized in Tables 4, 5, and 6.

The procedures used by the two Committees to evaluate reports were probably similar but more explicitly stated in the NIEHS Document.

3.5. Document organization

National Research Council document

This NRC Document consists of a detailed and comprehensive Executive Summary, followed by seven chapters: (1) Introduction, (2) Exposure and Physical Interactions, (3) Cellular and Molecular Effects, (4) Animal and Tissue Effects, (5) Epidemiology, (6) Risk Assessment, and (7) Research Needs and Research Agenda.

This document contains 14 figures and 53 tables with a massive amount of data summarized, especially in the appendix. The appendix also explains wire codes and residential exposure assessment. The NRC document has a glossary of terms and an index.

National Institute of Environmental Health Science document

The NIEHS Document consists of five chapters: (1) Introduction, (2) Occurrence and Measurement of Extremely Low Frequency Electromagnetic Fields, (3) Internal Dosimetry, (4) Biological Data Relating to the Toxicity of ELF Electromagnetic Fields, and (5) Final Summary and Evaluation.

Chapter 4 makes up the bulk of the book, approximately 300 pages, and provides a detailed account of biological data pertaining to EMF exposure. The data are considered under three main categories:

(*i*) **Cancer** in animals, adult humans, and children. The human cancer is based entirely on epidemiological data.

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(*ii*) **Non-Cancer Health Effects** in experimental animals, including effects on immunology, hematology, nervous system, reproduction and development, melatonin, and tissue repair; in human epidemiology, including occupational and residential exposure; in human laboratory studies, including perception, and effects on the central nervous system, cardiovascular system, neuroendocrine system, mood, and hypersensitivity.

(*iii*) **Mechanistic Effects** based on in vitro experiments and biophysics of EMF interactions.

At the end of each section the information is summarized. An additional summary, provided in Chapter 5 Final Summary and Evaluation, can be considered equivalent to an Executive Summary.

This document contains 9 figures and 63 tables, including information from many recent sources (post 1996). It also has abbreviations, a glossary, and two appendices (one is the IARC Monographs Programme, discussed below, and the other is the Minority Statement on Animal Carcinogenicity). There is neither an index nor a biographical sketch of the Working Group Members.

4. Executive summary

4.1. National Research Council executive summary

The overall conclusions of the NRC Expert Committee, as stated in the Executive Summary, are as follows (NRC 1997, p. 2):

> " ... the current body of evidence does not show that exposure to these fields presents a human health hazard. Specifically, no conclusive and consistent evidence shows that exposures to residential electric and magnetic fields produce cancer, adverse neurobehavioral effects or reproductive and developmental effects."
>
> " ... At exposure levels well above those normally encountered in residences, electric and magnetic fields can produce biologic effects (promotion of bone healing is an example), but these effects do not provide a consistent picture of a relationship between the biological effects of these fields and health hazards."
>
> "An association between residential wiring configuration (called wire codes, defined below) and childhood leukemia persists in multiple studies, although the causative factor responsible for that statistical association has not been identified. No evidence links contemporary measurements of magnetic-field levels to childhood leukemia."

Hence, two major biological effects linked to EMFs have been agreed upon. One is that very high fields, higher than those normally found in the home, can have biological effects, and the other is that only the wire codes associated with a residence have been statistically linked with childhood leukemia. The rest of the research in this area was deemed to be too inconsistent to warrant a link between EMF exposure and biological effects. Although the Committee noted that power frequency fields "have not been proven scientifically to be harmful, the panel recommends adoption of a policy of prudent avoidance" (NRC 1997, p. 19).

4.2. National Institute of Environmental Health Science executive summary

Members of the committee voted on the final summary and evaluations presented in chapter five, and the vote count is given with explanations for those who did not vote in favor of a particular statement. The majority report is accompanied by a Minority Statement on Animal Carcinogenicity in the appendix and is signed by five of the committee members (Table 2).

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Table 4. NIEHS evaluations and votes: summary of residential epidemiological studies (Chapter 4, NIEHS 1998 Report).

		Voting summary (number and percent)					
Response	Residential exposure: evaluation statement	Strong/ sufficient	Moderate/ limited	Weak/ inadequate	None/ lack of	Abstention	Absent
Cancer in children							
Cancer (all types)	There is *limited* evidence that residential exposure to ELF magnetic fields is carcinogenic to children.	0 0%	20 69%	6 21%	0 0%	2 7%	1 3%
Central nervous system	There is *inadequate evidence* with respect to childhood nervous system tumors.	0 0%	0 0%	25 86%	0 0%	2 7%	2 7%
Lymphoma	There is *inadequate evidence* with respect to childhood lymphoma.	0 0%	0 0%	25 86%	0 0%	2 7%	2 7%
Cancer in adults							
Cancer	There is *inadequate evidence* that residential exposure to extremely low frequency electromagnetic fields is carcinogenic to adults.	0 0%	0 0%	24 83%	1 3%	1 3%	3 10%
Non-cancer in adults							
Depression	There is *inadequate evidence* that environmental exposure to ELF EMF has adverse effects on pregnancy outcome or is associated with depression.	0 0%	0 0%	23 79%	1 3%	1 3%	4 14%
Hormones/ neurotransmitters	There is *weak evidence* that short term human exposure to ELF EMF causes changes in suppression of melatonin.	0 0%	1 3%	16 55%	2 7%	5 17%	5 17%
Sleep disturbance	There is *weak evidence* that short term human exposure to ELF EMF causes changes in sleep disturbance.	0 0%	0 0%	15 52%	0 0%	9 31%	5 17%
Cardiovascular system	There is *weak evidence* that short term human exposure to ELF EMF causes changes in heart-rate variability.	0 0%	1 3%	13 45%	2 7%	8 28%	5 17%

[a]29 members were eligible to vote.

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Table 5. NIEHS evaluations and votes: summary of occupational epidemiological studies (Chapter 4, NIEHS 1998 Report).

		Voting summary (number and percent)					
Response	Occupational exposure: evaluation statement	Strong/ sufficient	Moderate/ limited	Weak/ inadequate	None/ lack of	Abstention	Absent
Cancer in adults							
Chronic lymphocytic leukemia	There is *limited evidence* that occupational exposure to ELF magnetic fields is carcinogenic to adults. This evalutation is based on the results of studies of chronic lymphotic leukemia.	0 0%	14 48%	11 38%	0 0%	2 7%	2 7%
Other cancers	There is *inadequate evidence* for all other cancers.	0 0%	2 7%	22 76%	1 3%	2 7%	2 7%
Non-cancer in adults							
Amyotrophic lateral sclerosis	There is *inadequate evidence* that occupational exposure to ELF EMF causes amyotrophic lateral sclerosis.	0 0%	0 0%	24 83%	0 0%	1 3%	4 14%
Cardiovascular disease	There is *inadequate evidence* that occupational exposure to ELF EMF causes cardiovascular disease.	0 0%	0 0%	24 83%	0 0%	1 3%	4 14%
Alzheimer disease	There is *inadequate evidence* that occupational exposure to ELF EMF causes Alzheimer disease.	0 0%	0 0%	23 79%	1 3%	1 3%	4 14%
Reproduction and development	There is *inadequate evidence* that **maternal** occupational exposure to ELF EMF causes adverse birth outcomes.	0 0%	0 0%	22 76%	2 7%	1 3%	4 14%
Reproduction	There is *inadequate evidence* that **paternal** occupational exposure to ELF EMF causes reproductive effects.	0 0%	0 0%	20 69%	3 10%	2 7%	4 14%
Depression	There is *inadequate evidence* that occupational exposure to ELF EMF causes suicide or depression.	0 0%	0 0%	17 59%	6 21%	2 7%	4 14%

[a]29 members were eligible to vote.

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Table 6. NIEHS evaluations and votes: summary of in vivo and in vitro studies (Chapter 4, NIEHS 1998 Report).

Response	Organism	In vivo and in vitro studies: valuation statement	Voting summary (number and percent)					
			Strong/ sufficient	Moderate/ limited	Weak/ inadequate	None/ lack of	Abstention	Absent
in vivo								
Perception	Animals	There is *strong evidence* that electric fields can be perceived.	18 62%	0 0%	0 0%	0 0%	2 7%	9 31%
Bone repair	Animals and humans	There is *strong evidence* that exposure to electric and magnetic fields affects bone repair and adaptation.	14 48%	5 17%	0 0%	0 0%	8 28%	2 7%
Melatonin	Rodents	There is *weak evidence* that exposure to electric and magnetic fields alters the levels of melatonin in rodents.	0 0%	9 31%	14 48%	0 0%	4 14%	2 7%
Neurology	Animals	There is *weak evidence* for the neurobehavioral, neuropharmacologiocal, neurophysiobiological, and neurochemical effects in electromagnetic fields.	0 0%	8 28%	9 31%	0 0%	3 10%	9 31%
Cancer	Animals	There is *inadequate evidence* in experimental animals for carcinogenicity from exposure to extremely low frequency electromagnetic fields.	0 0%	0 0%	19 66%	8 28%	1 3%	1 3%
Immune system	Animals	There is *no evidence* in experimental animals for effects of ELF EMF on the immune system.	0 0%	0 0%	6 21%	13 45%	1 3%	9 31%
Reproduction and development	Animals	There is *no evidence* in experimental animals for the reproductive and develpmental effects of exposure to sinusoidal magnetic fields.	0 0%	0 0%	3 10%	17 59%	8 28%	1 3%
Hematology	Rodents	There is *no evidence* that exposure to power-line frequency EMF affects the hematologicla parameters of rodents.	0 0%	0 0%	0 0%	17 59%	1 3%	11 38%

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Table 6. (*concluded*).

			Voting summary (number and percent)					
Response	Organism	In vivo and in vitro studies: valuation statement	Strong/ sufficient	Moderate/ limited	Weak/ inadequate	None/ lack of	Abstention	Absent
Melatonin	Sheep and baboons	There is *no evidence* that exposure to electric and magnetic fields affects the levels of melatonin in sheep or baboons.	0 0%	0 0 %	0 0%	14 48%	13 45%	2 7%
Soft tissue repair	Vertebrates	The Working Group *could not reach a conclusion* about whether exposure to electric and magnetic fields affects nervous and non-bone connective tissue repair and adaptation in vertebrates.	12 41%	10 34%	6 21%	0 0%	0 0%	1 3%
in vitro								
Mechanism	Animal cells	A limited number of well-performed studies provide *moderate evidence* for mechanically plausible effects of EMF greater than 0.1 mT (100 µT, 1000 MG) in vitro at endpoints generally regarded as reflecting the action of toxic agents.	0 0%	27 93%	0 0%	0 0%	2 7%	0 0%
Mechanism	Animal cells	There is *weak evidence* for an effect of fields lower than approximately 0.1 mT (100 µT, 1000 mG).	0 0%	0 0%	26 90%	0 0%	3 10%	0 0%

[a]29 members were eligible to vote.

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Wording of the evaluation related to risk of human carcinogenicity follows the protocol established by the International Agency for Research on Cancer (IARC). Agents (mixtures or exposure circumstances) are classified into four groups with decreasing probability of carcinogenicity as follows (NIEHS Report, modified from pages 498–499, emphasis is mine):

Group 1: The agent (mixture or exposure circumstances) **is carcinogenic** *to humans.*

This category is used when there is *sufficient* evidence of direct carcinogenicity in humans or when this evidence is considered *insufficient* but *strong* in exposed humans and *sufficient* in experimental animals.

Group 2A: The agent is **probably carcinogenic** *to humans.*

This category is used when there is *limited* evidence of carcinogenicity in humans but *sufficient* evidence in experimental animals and *strong* evidence that the carcinogenesis is mediated by a mechanism that also operates in humans.

Group 2B: The agent is **possibly carcinogenic** *to humans.*

This category is used when there is *limited* evidence of carcinogenicity in humans but *less than sufficient* evidence in experimental animals. It can also be used when the evidence is *inadequate* in humans but *sufficient* in experimental animals.

Group 3: The agent is **not classifiable** *as to its carcinogenicity to humans.*

This category is used when the evidence of carcinogenicity is *inadequate* in humans and *inadequate* or *limited* in experimental animals. An exception includes agents (mixtures) for which there is strong evidence that the mechanism, carcinogenicity in experimental animals, does *not operate* in humans.

Group 4: The agent is **probably not carcinogenic** *to humans.*

This category is used when there is evidence suggesting *lack of carcinogenicity* in humans and in experimental animals or *inadequate* evidence in humans but consistent and strong evidence suggesting *lack of carcinogenicity* in experimental animals.

The overall evaluation of the majority of the Working Group is that extremely low frequency EMF can be classified as “possibly carcinogenic” (Group 2B) and that this “is a conservative, public-health decision based on limited evidence of an increased risk for childhood leukemias with residential exposure and an increased occurrence of CLL (chronic lymphocytic leukemia) associated with occupational exposure. For these particular cancers, the results of in vivo, in vitro, and mechanistic studies do not confirm or refute the findings of the epidemiological studies.” (NIEHS 1998, p. 402).

They go on to state that “Because of the complexity of the electromagnetic environment, the review of the epidemiological and other biological studies did not allow precise determination of the specific, critical conditions of exposure to ELF EMF associated with the disease endpoints studied.” (NIEHS Report, p. 400).

The NIEHS Report also provides the results of their specific deliberations as shown in Tables 4, 5, and 6). Committee members (29 eligible) voted that the evidence to support a particular statement was either A, strong/sufficient; B, moderate/limited; C, weak/inadequate; or D, non-existent. According to these tables the areas of greatest agreement are as follows:

A. There is **strong /sufficient** evidence that:

- A-1 electric fields can be perceived (62% voted in favor of statement, 31% were absent).
- A-2 exposure to electric and magnetic fields affects bone repair and adaptation (48% vote with 28% abstentions).

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B. There is **moderate/limited** evidence that:

B-1 mechanistically plausible toxic effects of EMF greater than 0.1 mT (100 μT, 1000 mG) have been demonstrated in vitro (93% vote).

B-2 B-2 residential exposure to ELF magnetic fields is carcinogenic to children (69% vote).

B-3 occupational exposure to ELF magnetic fields causes chronic lymphocytic leukemia (CLL) in adults (48% vote).

C. There is **weak /inadequate** evidence that:

C-1 electric fields lower than approximately 0.1 mT (100 μT, 1000 mG) have effects in vitro (90%).

C-2 residential exposure is associated with childhood nervous system tumors (86%) and childhood lymphoma (86%).

C-3 residential exposure to extremely low frequency EMF is carcinogenic to adults (83%).

C-4 occupational exposure to ELF magnetic fields causes cancers (other than CLL) (76%); amyotrophic lateral sclerosis (83%); Alzheimer disease (79%).

C-5 environmental exposure to ELF EMF has adverse effects on pregnancy outcome or is associated with depression (79%).

C-6 maternal (76%) and paternal (60%) occupational exposure to ELF EMF causes reproductive effects.

C-7 exposure to ELF EMF is carcinogenic to experimental animals (66%).

C-8 occupational exposure to ELF EMF causes suicide or depression (59%).

C-9 short-term human exposure to ELF EMF suppresses melatonin (55%), causes sleep disturbance (52%); changes heart-rate variability (45%).

C-10 exposure to electric and magnetic fields alters the levels of melatonin in rodents (48%).

C-11 electromagnetic fields cause neurobehavioral, neuropharmacologic, neurophysiological, and neurochemical effects in vivo (31%).

D. There is a **lack** of evidence that:

D-1 exposure to sinusoidal magnetic fields affects reproduction and development in vivo (59%).

D-2 exposure to power-line frequency EMF affects hematological parameters of rodents (59%).

D-3 exposure to electric and magnetic fields alters levels of melatonin in sheep or baboons (48%).

D-4 exposure to EMF affects the immune system in vivo (45%).

The Committee was unable to reach a conclusion on the effectiveness of EMF for soft tissue repair in vertebrates.

My interpretation of the voting is that it was conservative, erring on the side of “no effect.” The evidence is considerably stronger than appears in this evaluation if a much broader literature is examined.

In section A above, neither statement is controversial. Electric fields **can** be perceived (Chatterjee et al. 1986) and electric and magnetic fields **do** promote bone repair and have been clinically used for years (Bassett 1995). There is evidence that magnetic fields can also be perceived by several species (bees, birds, turtles, for example), although studies with humans are inconclusive (Blakemore 1975; Larkin and Sutherland 1977; Gould et al. 1978; Walcott et al. 1979, see also excellent review by Kholodov et al. 1990).

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I do not agree with either statement B-2 or B-3 that epidemiological evidence indicates a **causal** relationship between EMF exposure and childhood and adult cancer. What has been documented is an **association** between extremely low frequency EMF and some forms of childhood and adult cancer. The association seems to be one of promotion rather than initiation. An uncritical reader may interpret this statement to mean that ELF EMFs initiate cancer and that conclusion would be false based on the evidence available.

Regarding statement B-1, I would go further and suggest that plausible mechanisms for toxic effects of EMFs have been demonstrated. Studies have shown suppression of night-time melatonin between 0.2 and 1.2 μT (Liburdy et al. 1993), altered calcium flux at various intensities (Bawin and Adey 1976; Blackman et al. 1979; Dutta et al. 1989); chromosomal aberrations at 30 μT of intermittent or pulsed exposure (Nordenson et al. 1994); altered ornithine decarboxylase activity (ODC in its signal transduction role) at 1, 10, and 100 μT (Litovitz et al. 1991); increased cell proliferation above 100 μT (Liburdy et al. 1993; Katsir et al. 1998), and tumor initiation in two human cell lines following short (2 h) exposure to 400 mT (Miyakoshi et al. 1996; Miyakoshi et al. 1998).

Of the statements for which the evidence is classified as “weak or inadequate,” I would suggest that the evidence for some (C-2, 5, 9, and 11) is “moderate or limited.” Breast cancer is not specifically mentioned in C-4, which is unusual since this is one area where epidemiological, in vivo and in vitro studies seem to suggest that EMF effects on night-time melatonin may stimulate estrogen-responsive breast cancer cells (Liburdy et al. 1993).

4.3. Conclusions regarding electric and magnetic field exposure and biological effects

My own conclusions, based on NRC and NIEHS Documents as well as on references covering a much broader scope are as follows:

(1) low frequency electric and magnetic fields, separately and in combination, **can** affect living organisms.

(2) effects can be **neutral**, **harmful**, or **beneficial**,

(3) effects can occur at **low intensities**, commonly found in residential settings, and some effects are intensity specific (intensity windows).

(4) effects can occur at **low frequencies,** at, above, and below the power distribution frequencies and some effects are frequency specific (frequency windows).

(5) **timing** of exposure (day vs. night, for example) is critical for some effects (time windows).

(6) **location** of exposure (as it relates to the geomagnetic field) is important for some effects.

(7) **sensitivities** to EMFs vary enormously, express themselves in different ways, and may be initiated by EMF exposure or chemical exposure.

(8) numerous species (bacteria, insects, birds, reptiles, fish, mammals) are able to **detect** and respond to changes in electromagnetic fields and this detection has adaptive significance.

(9) we understand some of the **mechanisms** responsible and are at the threshold of understanding others that are involved.

(10) the **classical toxicological model** of dose/response may be inappropriate for electric and magnetic field exposure.

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5. Exposure

Ed Leeper, who co-authored the seminal paper on childhood cancers and power lines (Wertheimer and Leeper 1979), reasoned that in a residential setting the magnetic component of the electromagnetic fields was likely to be the most important biologically since the electric component is blocked by buildings and trees. He also reasoned that the strength of the magnetic field was likely to be a function of the number of residents serviced (current) and the distance between lines and transformers to individual homes. He devised a wire code that included both of these factors (Fig. 3). The Wertheimer and Leeper (1979) study, and many since, have relied on wire codes as a surrogate for magnetic field measurements.

As instrumentation for measuring weak, low frequency magnetic fields became more readily available, wire codes were supplemented by the spot measurement. The spot measurement is useful in a setting with a constant magnetic field, at a specific distance from an appliance for instance. However, in a residential setting the magnetic field fluctuates normally with a bimodal peak in the morning and evening corresponding to maximum power use.

A more precise measurement for a fluctuating magnetic field is a time-integrated measurement, often done in a residential setting for a 24-h period and in an occupational setting for the duration of the work day. These integrated monitors can be placed in a specific location or worn as personal monitoring devices. With each improvement in our ability to precisely measure the magnetic flux density, we have become aware of the dynamic nature of our electromagnetic environment.

5.1. Residential exposure

In a residential setting there are three major sources of technologically generated magnetic fields: the outdoor distribution system consisting of either below ground or above ground wires and transformers (as represented by the wire code); the indoor distribution system consisting of indoor wiring and grounding; and appliances. The early studies assumed that power lines provided the major source of magnetic fields inside the home and both indoor wiring and appliance use were ignored. More recent studies enable us to calculate TWA (time-weighted average) magnetic flux densities for a given environment (see Components of Residential Exposure).

Outdoor distribution system

Wire codes may provide a good relative surrogate for the magnetic flux density within a community. However, they become less reliable when different communities are compared. Table 7 shows the magnetic flux densities associated with wire codes for different studies. If we assume, for the moment, that the magnetic flux density in Table 7 is due entirely to the outdoor power distribution system we can see that the magnetic flux density can range from 0.02 to 8.7 μT. Within each wire code category, the magnetic flux density (as measured by spot measurements and 24-h measurements) can differ considerably between studies leading to considerable overlap. This is one of the inherent weaknesses with respect to wire codes. So, while a comparison of wire codes within a community is useful, comparison of wire codes for different communities has limitations.

The electric field was not considered to be important in the residential epidemiological studies. Unlike the 15 to 25 kV/m electrical potentials in 500 kV switchyards, electric fields immediately beneath overhead neighborhood distribution lines are likely to be less than 30 V/m (unpublished data). However, there is a trend among electric utilities to increase the voltage of power distribution lines to minimize energy loss due to resistance. Power transmission lines lose approximately 1% per 100 miles and loss of power due to resistance has been calculated to be between 5 and 10% per year. The cost of this is considerable. By increasing the voltage, resistance drops as does power loss. So this move to higher voltage makes economic sense. However, as voltage increases so does the intensity of the electric field, and studies have now shown that the harmful effects associated with magnetic field exposure may be worse in the presence of a strong electric field (Miller et al. 1996).

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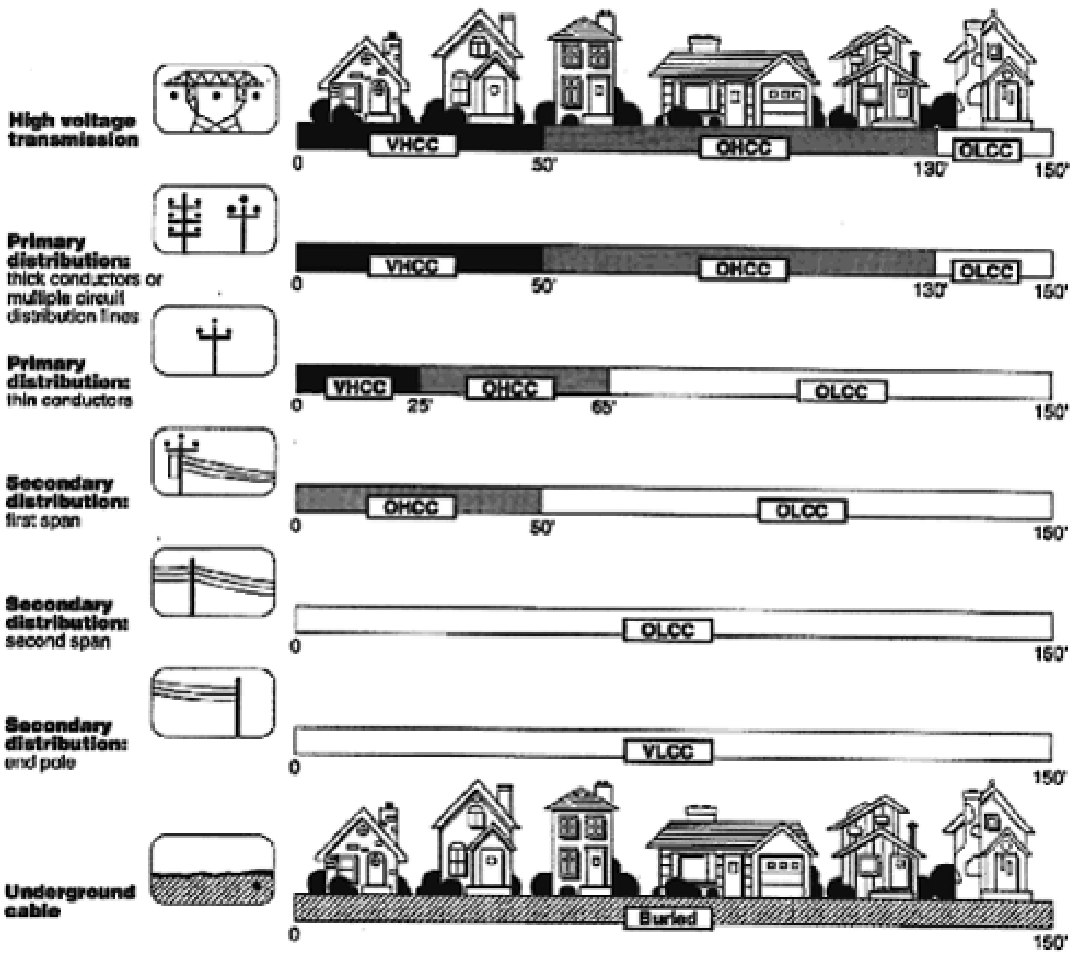
Fig. 3. A simplified schematic of the basic features of the differences in the wire codes as defined to support epidemiological studies. VHCC, OHCC, OLCC, VLCC stand for very high, ordinary high, ordinary low, and very low current configurations. (Reprinted with permission from *Possible health effects of exposure to residential electric and magnetic fields.* Copyright 1997 by the National Academy of Sciences. Courtesy of the National Academy Press. Washington, D.C.)



Indoor distribution system

Indoor wiring is another important source of magnetic fields in the home. Within a properly wired building far from a power line normal fields should not exceed 0.03 μT and even this low field would be due to fluorescent lights (Riley 1995). In a building with faulty wiring or with older knob and tube wiring, fields may be 0.2 to 3 μT and even higher near walls, ceilings, and floors (Bennett 1994; Riley 1995).

The EPRI (1993 as cited in NIEHS 1998) conducted a survey of 1000 homes and took both 24-h and spot measurements in different rooms. A summary of the results (Table 8) shows that median magnetic flux densities for 24-h measurements vary more than 10-fold with 50% of the homes exceeding 0.05 μT (and 1% of the homes exceeding 0.55 μT). The highest wire code category (VH) in the Wertheimer and Leeper (1982) study was 0.25 μT and according to the EPRI study, 5% of the homes exceeded this value. Note also that the 24-h measurement includes the combined field from power lines and grounding system.

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Table 7. Magnetic flux density associated with wire codes (based on Table 2.1, p. 28, NRC 1997; Tables 2.7 and 2.9, pp. 76 and 36, NIEHS 1998).

Source	Power source and measurement	Distance (ft)	Distance (m)	Magnetic flux density (μT)		
Very high (VH)						
High Voltage Transmission Lines	500 kV	0	0	8.7		
High Voltage Transmission Lines	230 kV	0	0	5.8		
High Voltage Transmission Lines	115 kV	0	0	3		
High Voltage Transmission Lines	500 kV	50	15	2.9	Max.	8.7
High Voltage Transmission Lines	230 kV	50	15	2	Median	0.48
High Voltage Transmission Lines	115 kV	50	15	0.7	Min.	0.11
Wertheimer and Leeper 1982	Median	50	15	0.25		
Savitz et al. 1988	Low pwr spot: mdn	50	15	0.22		
Severson et al. 1988	Small subsample	50	15	0.17		
Tarone et al. 1988	24-h means: mdn	50	15	0.13		
Preston-Martin et al. 1996*b*	24-h bedrm mean: mdn	50	15	0.11		
London et al. 1991	24-h median: GM	50	15	0.11		
Ordinary high (OH)						
High Voltage Transmission Lines	500 kV	100	30	1.3		
High Voltage Transmission Lines	230 kV	100	30	0.7		
High Voltage Transmission Lines	115 kV	100	30	0.2		
Wertheimer and Leeper 1982	Median	130	40	0.12	Max.	1.3
Severson et al. 1988	Small subsample	130	40	0.11	Median	0.11
Tarone et al. 1988	24-h means: mdn	130	40	0.1	Min.	0.06
Savitz et al. 1988	Low pwr spot: mdn	130	40	0.09		
London et al. 1991	24-h median: GM	130	40	0.07		
Preston-Martin et al. 1996*b*	24-h bedrm mean: mdn	130	40	0.06		
Ordinary low (OL)						
High Voltage Transmission Lines	500 kV	200	60	0.32		
High Voltage Transmission Lines	230 kV	200	60	0.18		
Tarone et al. 1988	24-h means: mdn	150	50	0.08		

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Table 7. (*concluded*).

Source	Power source and measurement	Distance (ft)	Distance (m)	Magnetic flux density (μT)		
London et al. 1991	24-h median: GM	150	50	0.06	Max.	0.32
Savitz et al. 1988	Low pwr spot: mdn	150	50	0.05	Median	0.05
Wertheimer and Leeper 1982	Median	150	50	0.05	Min.	0.04
Severson et al. 1988	Small subsample	150	50	0.05		
Preston-Martin et al. 1996*b*	24-h bedrm mean: mdn	150	50	0.04		
High Voltage Transmission Lines	115 kV	200	60	0.04		
Very low (VL)						
High Voltage Transmission Lines	500 kV	300	90	0.14		
High Voltage Transmission Lines	230 kV	300	90	0.08		
Preston-Martin et al. 1996*b*	24-h bedrm mean: mdn	150	50	0.06		
Wertheimer and Leeper 1982	Median	150	50	0.05	Max.	0.14
Tarone et al. 1988	24-h means: mdn	150	50	0.05	Median	0.05
London et al. 1991	24-h median: GM	150	50	0.04	Min.	0.02
Severson et al. 1988	Small subsample	150	50	0.03		
Savitz et al. 1988	Low pwr spot: mdn	150	50	0.03		
High Voltage Transmission Lines	115 kV	300	90	0.02		
Underground (UG)						
Preston-Martin et al. 1996*b*	24-h bedrm mean: mdn	150	50	0.05		
Tarone et al. 1988	24-h means: mdn	150	50	0.05	Max.	0.047
London et al. 1991	24-h median: GM	150	50	0.05	Median	0.046
Savitz et al. 1988	Low pwr spot: mdn	150	50	0.03	Min.	0.03

Note: Low pwr spot = low power spot measurement, field measured with appliances turned off; mdn = median; GM = geometric mean; bedrm = bedroom.

The spot measurements for magnetic flux density differed in rooms and some were sufficiently high to suggest faulty wiring. Rooms with the highest average spot measurements ranged from 0.11 μT (50th percentile, 50% of the homes exceeded this value) to 1.22 μT (99th percentile, 1% of the homes exceeded this value). A personal 24-h monitoring device offers the most reliable estimate of exposure. However, to identify sources of the magnetic field, multiple indoor and outdoor measurements are necessary.

Improperly installed indoor wiring can account for very high fields. In a survey of 150 buildings, Riley (1995) reported that 66% of the high fields above 3 mG (0.3 μT) were due to wiring and grounding problems, 18% were due to the proximity to power lines, and 3% were due to appliances. Of the wiring problems, 12% were due to knob-and-tube wiring used in older buildings, 22% were due to improper grounding to the plumbing system, and 65% were due to wiring violations. Knob-and-tube is a system of wiring used until the 1940s. The hot and neutral conductors are separated by several inches to several

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Table 8. Estimated magnetic flux density based on spot measurements and 24-h measurements in the 1000 homes survey (NIEHS 1998, Table 2.9, p. 36).

	60-Hz magnetic flux density (μT)					
	Spot measurements[a]					24-h measurement[b]
				All rooms		All rooms
% of homes in which values were exceeded	Kitchen	Bedrooms	Highest[c]	Mean	Median	Median
50	0.07	0.05	0.11	0.06	0.05	0.05
25	0.12	0.1	0.21	0.11	0.1	0.1
15	0.24	0.2	0.38	0.21	0.17	0.18
5	0.35	0.29	0.56	0.3	0.26	0.26
1	0.64	0.77	1.22	0.66	0.58	0.55

[a]Data from 992 residences.
[b]Data from 986 residences; combined field from power-line and grounding system.
[c]Room with highest spot reading.

feet. The greater the separation the higher the magnetic field that is produced and the less it decreases with distance ($1 \times r^{-1}$ for a single line conductor rather than $1 \times r^{-2}$ for close parallel line conductors).

Common wiring faults that lead to large magnetic fields include neutral to ground connections, separation of conductors (as with knob-and-tube wiring), grounding to water pipes, and parallel neutrals (i.e., neutrals from different circuits connected together on the load side of the breaker box) (Riley 1995).

One common source of higher magnetic fields is the use of extra ground connections through water pipes. According to Bennett (1994) rerouting or adding ground return wires can produce background magnetic fields in the order of 1 μT in the home.

While we might assume that our indoor exposure to magnetic fields has increased with our increasing reliance on electrical appliances, older homes (pre-1940) with knob-and-tube wiring can generate substantial magnetic fields. Knob-and-tube wiring with wires spaced 6 in. (15 cm), carrying a current of 20 A (rms), can produce a magnetic field of 0.61 μT at a distance of 1 m (Bennett 1994). If the wires are closer together (2.5 in. or 6.3 cm) the field is reduced to 0.25 μT. Modern wiring (such as Romex or a twisted pair of BX cables), carrying the same current, produces even lower fields of 0.03 to <0.01 μT, respectively, (Bennett 1994).

Based on the preliminary results from the 1000 home survey presented at a conference, Riley noted that the magnetic flux density increased with age of dwelling. The older homes (>50 years) had an average magnetic flux density of 0.082 μT while the newer homes (<10 years) had 0.038 μT. In attempting to verify this I requested a copy of the industry-funded EPRI study. I was informed that the report is available free to industrial partners who funded the research and can be purchased by others for $20 000 in US funds for each of two volumes. The preliminary report is available for $2000 US per volume. This extraordinarily high price has made the report inaccessible to non-utility scientists and others interested in the results, a most unfortunate consequence. This pricing policy obviously has nothing to do with protecting patent rights nor is it an attempt to raise money, since libraries cannot afford such prices for individual volumes. The only conclusion one can draw is that the power industry does not want to make this information publicly available.

Appliances

The EPA (1992) measured the magnetic fields produced by a variety of household and office appliances (Table 9). According to this study, the magnetic fields generated by appliances differ enormously and drop off rapidly (generally $1 \times r^{-3}$) with distance. Magnetic flux densities, in Table 9 range from

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Table 9. Magnetic flux density of common household and office appliances. (from EPA 1992, in Levitt 1995, pp. 254–258 and from US Food & Drug Adminisration, in Q&A about EMF 1995, p. 42).

			Magnetic flux density (μT)			
	Distance	~cm	15	30	60	120
Room/source	from source	ft	0.5	1	2	4
Bathroom						
Electric shavers		Low	0.4	—	—	—
		Median	10	2	—	—
		High	60	10	1	0.1
Hair dryers		Low	0.1	—	—	—
		Median	30	0.1	—	—
		High	70	7	1	0.1
Bedroom						
Analog clocks (conventional face)		Low	—	0.1	—	—
		Median	—	1.5	0.2	—
		High	—	3	0.5	0.3
Digital clocks		Low	—	—	—	—
		Median	—	0.1	—	—
		High	—	0.8	0.2	0.1
Baby monitor		Low	0.4	—	—	—
		Median	0.6	0.1	—	—
		High	1.5	0.2	—	—
Electric blanket (conventional)[a]		Average	2.2	5 cm distance		
		High	3.9	5 cm distance		
Electric blanket (PTC)[a, b]		Average	0.09	5 cm distance		
		High	0.27	5 cm distance		
Kitchen						
Blenders		Low	3	0.5	—	—
		Median	7	1	0.2	—
		High	10	2	0.3	—
Can openers		Low	50	4	0.3	—
		Median	60	15	2	0.2
		High	150	30	3	0.4
Coffee makers		Low	0.4	—	—	—
		Median	0.7	—	—	—
		High	1	0.1	—	—
Crock-pots		Low	0.3	—	—	—
		Median	0.6	0.1	—	—
		High	0.9	0.1	—	—

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Table 9. (*continued*).

			Magnetic flux density (μT)			
Room/source	Distance from source	~cm ft	15 0.5	30 1	60 2	120 4
Dishwashers		Low	1	0.6	0.2	—
		Median	2	1	0.4	—
		High	10	3	0.7	0.1
Electric ovens		Low	0.4	0.1	—	—
		Median	0.9	0.4	—	—
		High	2	0.5	0.1	—
Electric ranges		Low	2	—	—	—
		Median	3	0.8	0.2	—
		High	20	3	0.9	0.6
Food processors		Low	2	0.5	—	—
		Median	3	0.6	0.2	—
		High	13	2	0.3	—
Garbage disposals		Low	6	0.8	0.1	—
		Median	8	1	0.2	—
		High	10	2	0.3	—
Microwave ovens		Low	10	0.1	0.1	—
		Median	20	4	1	0.2
		High	30	20	3	2
Mixers		Low	3	0.5	—	—
		Median	10	1	0.1	—
		High	60	10	1	—
Refrigerators		Low	—	—	—	—
		Median	0.2	0.2	0.1	—
		High	4	2	1	1
Toasters		Low	0.5	—	—	—
		Median	1	0.3	—	—
		High	2	0.7	—	—
Living/family room						
Air conditioners (window)		Low	—	—	—	—
			—	0.3	0.1	—
		High	—	2	0.6	0.4
Ceiling fan		Low			—	—
		Median		0.3	—	—
		High		5	0.6	0.1
Black and white TVs		Low		0.1	—	—
		Median		0.3	—	—
		High		1	0.2	0.1

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Table 9. (*continued*).

Room/source	Distance from source	~cm / ft	15 / 0.5	30 / 1	60 / 2	120 / 4
			Magnetic flux density (μT)			
Colour TVs		Low		—	—	—
		Median		0.7	0.2	—
		High		2	0.8	0.4
Tuners/tape players (including VCRs)		Low	—	—	—	—
		Median	0.1	—	—	—
		High	0.3	0.1	—	—
Laundry room						
Electric clothes dryers		Low	0.2	—	—	—
		Median	0.3	0.2	—	—
		High	1	0.3	—	—
Washing machines		Low	0.4	0.1	—	—
		Median	2	0.7	0.1	—
		High	10	3	0.6	—
Irons		Low	0.6	0.1	—	—
		Median	0.8	0.1	—	—
		High	2	0.3	—	—
Vacuum cleaners		Low	10	2	0.4	—
		Median	30	6	1	0.1
		High	70	20	5	1
Office						
Air cleaners		Low	11	2	0.3	—
		Median	18	3.5	0.5	0.1
		High	25	5	0.8	0.2
Copy machines		Low	0.4	0.2	0.1	—
		Median	9	2	0.7	0.1
		High	20	4	1.3	0.4
Fax machines		Low	0.4	—	—	—
		Median	0.6	—	—	—
		High	0.9	0.2	—	—
Fluorescent lights		Low	2	—	—	—
		Median	4	0.6	0.2	—
		High	10	3	0.8	0.4
Electric pencil sharpeners		Low	2	0.8	0.5	—
		Median	20	7	2	0.2
		High	30	9	3	0.3

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Table 9. (*concluded*).

			Magnetic flux density (μT)			
	Distance	~cm	15	30	60	120
Room/source	from source	ft	0.5	1	2	4
Video-display terminals (PCs with colour monitors)		Low	0.7	0.2	0.1	—
		Median	1.4	0.5	0.2	—
		High	2	0.6	0.3	—
Battery chargers		Low	0.3	0.2	—	—
		Median	3	0.3	—	—
		High	5	0.4	—	—
Portable heaters		Low	0.5	0.1	—	—
		Median	10	2	0.4	—
		High	15	4	0.8	0.1
Power drills		Low	10	2	0.3	—
		Median	15	3	0.4	—
		High	20	4	0.6	—
Power saws		Low	5	0.9	0.1	—
		Median	20	4	0.5	—
		High	100	30	4	0.4

[a]Data from the Centre for Devices and Radiological Health, USFDA.
[b]PTC = positive temperature coefficient (low-magnetic field electric blankets).

150 μT for can openers to less than 0.1 μT for tape players. There are considerable model differences as well. For example, hair dryers can range from a high of 70 μT to a low of 0.1 μT depending on make and model.

The appliances of greatest concern are those with high magnetic flux densities and long exposure times. Electric blankets, for example, generate a field of 2 to 4 μT and are in contact with the body for several hours each night. New models, known as the positive temperature coefficient electric blankets, now generate magnetic fields that are one tenth or lower than those generated by the older models. Hair dryers and electric shavers generate a high magnetic field near the head. Power saws generate high magnetic fields and they may be of concern for the professional carpenter.

One metric that might have biological significance is cumulative exposure. This depends on three variables: the magnetic flux density of the appliance, distance at which it is used, and the duration of exposure. Based on Table 9 we can estimate daily exposure if we make certain assumptions about appliance use.

One series of assumptions is provided in Table 10. This table includes nine appliances commonly used in North America. For each appliance a high and low magnetic flux density (based on the EPA 1992 study) is calculated for two models, two distances, and two exposures to provide a maximum and minimum value. The sum of these gives eight daily cumulative exposures for appliance use. These range from a low of 0.37 to a high of 165 μT·h (an almost 500-fold difference). Hence individuals living in the same house may be exposed to very different magnetic flux densities attributable entirely to use of appliances.

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Components of residential exposure

Based on an estimate of the magnetic flux density associated with appliance use, indoor wiring, and the outdoor distribution lines, we can calculate the relative contribution of each of these sources (see Table 11).

In Example A, for properly wired newer homes (low field) far from outdoor power lines (low field), appliances are likely to be the major residential source and may account for more than 60% of magnetic field exposure (Table 11).

In Example B, in new homes (low field) near power lines (high field), external sources are likely to be considerable (>80%) with low appliance use and measurable (10–30%) with moderate to high appliance use (refer to Table 10 for characterization of appliance use and Table 11 for examples A to D).

In Example C, in older homes (or homes with faulty wiring) (high field) far from external sources (low field), indoor wiring is likely to be the major source of magnetic field exposure (>50%) if appliance use is moderate to low. Indoor wiring can also contribute measurably to exposure (>10%) when appliance use is high.

In Example D, in older homes (high field) near external power lines (high field), both indoor and outdoor wiring become significant sources (>30 %) of magnetic field exposure and except for the highest appliance use, they can account from 20% to 97% of exposure in a residential setting.

According to these calculations maximum daily cumulative exposure can be attributed to appliances, indoor wiring, or outdoor power lines depending on the circumstances. Also, individuals living in the same residence may be exposed to different magnetic fields based on the amount of time and type of appliances they use and the time they spent in various rooms. These differences, not considered in the early epidemiological studies, may account for some of the discrepancy in the results. Future epidemiological studies should take them into consideration.

Data from personal monitoring devices indicate the variability of the electromagnetic environment. Measurements of the 24-h magnetic flux for a 9-year-old girl in California showed values varied from less than 0.05 to 0.4 μT at home after school. They increased to a high of 0.7 μT during the early part of the night when she slept under an electric blanket. At school, the following day, background values were low (approximately 0.05 μT) although several peaks, many of them with unidentifiable sources, exceeded 2 μT (Hitchcock and Patterson 1995). These data are disturbing if you consider that values of 0.2 μT and higher have been linked with excess cases of childhood leukemia (Michaelis et al. 1998; Savitz et al. 1988; Olsen et al. 1993).

5.2. Occupational exposure

Just as the early residential epidemiological studies used wire codes as surrogates for magnetic fields, the early occupational epidemiological studies initially based their result on job titles. As interest in occupational exposure increased, more measurements of magnetic fields in various occupational settings and associated with individual exposure began to be documented. Because of the variability within and among occupations as well as between types of measurements (spot measurement vs. time weight averages), comparisons of occupations is difficult and can only be considered tentative at this time.

Personal monitoring of workers provides the most information and, in the long term, may prove to be the most useful measurement. Examples of four occupations, in Fig. 4, demonstrate the variability of EMF exposure. These examples should not be interpreted as typical EMF exposures for these occupations.

The National Institute of Environmental Health Science (NIEHS1998) accumulated a vast amount of data for time weighted average magnetic field exposures, which has been summarized according to industry type in Table 12. The original data were ranked in decreasing order of exposure and classified into percentile groupings. The 95th percentile was at 0.66 μT and can be considered very high exposure

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Table 10. Time-weighted daily magnetic flux density calculated for short and long exposure at two distances for each of nine appliances found in the home (based on data in Table 9).

		Distance				Time-weighted magnetic flux density (μT·h)			
		Near		Far		Near		Far	
Appliance exposure time (short and long)	Appliance magnetic field	(cm)	(μT)	(cm)	(μT)	Long	Short	Long	Short
Hair dryers	Low	15	0.1	30	0.01	0.0083	0.0033	0.0008	0.0003
(2 and 5 min)	High		70		7	5.81	2.31	0.581	0.231
Analog clocks	Low	30	0.1	60	0.01	0.8	0.6	0.08	0.06
(6 and 8 h)	High		3		0.5	24	18	4	3
Electric blanket	Low	5	0.01	5	0.01	0.08	0.06	0.08	0.06
(6 and 8 h)	High		3.9		3.9	31.2	23.4	31.2	23.4
Microwave ovens	Low	30	0.1	120	0.01	0.0083	0.0017	0.0008	0.0002
(1 and 5 min)	High		20		2	1.66	0.34	0.166	0.034
Colour TVs	Low	60	0.01	120	0.01	0.04	0.01	0.04	0.01
(1 and 4 h)	High		0.8		0.4	3.2	0.8	1.6	0.4
Air cleaners	Low	30	2	60	0.01	16	4	0.08	0.02
(2 and 8 h)	High		5		0.2	40	10	1.6	0.4
Fluorescent lights	Low	30	0.01	60	0.01	0.08	0.02	0.08	0.02
(2 and 8 h)	High		3		0.4	24	6	3.2	0.8
Video-display terminals	Low	30	0.2	60	0.1	0.8	0.1	0.4	0.05
(0.5 and 4 h)	High		0.6		0.3	2.4	0.3	1.2	0.15
Power saws	Low	15	5	30	0.9	1.65	0.85	0.297	0.153
(10 and 20 min)	High		100		30	33	17	9.9	5.1
All appliances	Low	Daily sum (μT·h)				19.5	5.6	1.1	0.37
	High					165.3	78.2	53.4	33.5
All appliances	Low	Function of lowest exposure				53	15	3	1
	High					447	211	144	91

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Table 11. Relative contribution of appliances, indoor wiring, and outdoor wiring to the daily magnetic field exposure in a residential setting.

		Daily magnetic field exposure (percent of total residential exposure)											
		Example A			Example B			Example C			Example D		
Indoor wiring[a]:	⟶	LOW			LOW			HIGH			HIGH		
Outdoor wiring[b]:	⟶	LOW			HIGH			LOW			HIGH		
Appliances[c]	Time	Appl[d]	Indoor wiring[a]	Outdoor wiring[b]	Appl[d]	Indoor wiring[a]	Outdoor wiring[b]	Appl[d]	Indoor wiring[a]	Outdoor wiring[b]	Appl[d]	Indoor wiring[a]	Outdoor wiring[b]
LOW	Short	34	22	44	6	4	91	5	89	6	3	53	44
	Long	60	13	26	15	3	82	13	82	5	8	50	42
MODERATE	Short	89	4	8	47	2	51	42	54	4	30	38	32
	Long	96	1	2	76	1	23	72	26	2	60	22	18
HIGH	Short	98	1	1	84	1	15	81	17	1	72	15	13
	Long	99	0	1	90	0	10	87	12	1	80	11	9
VERY HIGH	Short	99	0	1	93	0	7	91	8	1	86	8	7
	Long	100	0	0	96	0	3	96	4	0	93	4	3

[a]Indoor wiring: LOW, properly wired newer home = 0.01 μT (0.24 μT·h for 24 h exposure); HIGH, older home with knob and tube wiring and/or with faulty wiring = 0.3 μT (7.2 μT·h for 24 h exposure) (Bennett 1994; Riley 1994).

[b]Outdoor wiring: LOW, very low current configuration, 0.02 μT (0.48 μT·h for 24 h exposure); HIGH, very high current configuration, 0.25 μT (6 μT·h for 24 h exposure) (Wertheimer and Leeper 1982).

[c]Appliance code: LOW, appliance with low magnetic flux density, far exposure; MODERATE, appliance with low magnetic flux density, near exposure; HIGH, appliance with high magnetic flux density, far exposure; VERY HIGH, appliance with high magnetic flux density, near exposure.

[d]Based on data in Tables 9 and 10.

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with only 5% of the work force exposed to higher TWA magnetic fields. The 75th percentile was at 0.27 μT and is close to the values associated with very high current configuration (VH) for power lines (Wertheimer and Leeper 1982). The median (50th %) TWA magnetic flux density was at 0.17 μT and the 25th percentile was at 0.12 μT. These percentile rankings are also presented in Table 12 and are associated with considerable variability. Similar results can be seen for various occupations in Table 13.

Despite the variability of occupational exposure, some general conclusions can be drawn. For instance, some of the highest exposures occur in the textile, utility, transportation, and metallurgical industries. Among textile works, dressmakers and tailors who use industrial sewing machines are exposed to some of the highest fields. In the utility industry, linemen, electricians, cable splicers, as well as power plant and substation operators are among those with the highest magnetic field exposure. In transportation, railway workers have high exposures. Among metal workers, welders, and those who do electrogalvanizing or aluminum refining (Table 14) tend to have high magnetic field exposure .

Another industry with notable exposure is telecommunications, especially telephone linemen, technicians, and engineers. Individuals repairing electrical and electronic equipment can also be exposed to above average magnetic fields, as can dental hygienists and motion picture projectionists (Tables 12–14).

In an office environment, magnetic fields are generally at or below average ($\leq$0.17 μT), except near computers, photocopiers, or other electronic equipment (Table 14). People in sales, in computer services and in the construction industry are generally exposed to lower magnetic fields.

According to Table 12, teachers were below average with a TWA magnetic flux density of 0.15 μT. This is twice as high as the average magnetic flux densities of 0.082 μT reported for Canadian schools (Sun et al. 1995). Schools, particularly elementary schools, are of concern because of the time young children spend in these environments. Where and when a measurement is taken is important if you consider the highly fluctuating environment, as previously presented, for the 9-year-old girl at school.

Normally we think of high EMF exposure only or primarily in electrical occupations and perhaps in an office setting with computers and copy machines. However, a number of occupations not normally classified “electrical” can be exposed to high EMFs. These include some of the professions already mentioned (tailors and seamstresses, metal workers, and medical technicians), but they can also include airplane pilots, streetcar and train conductors, hair dressers, and professional carpenters.

Hairdressers use hand-held hair dryers for several hours each day. A 2-h exposure to a high-intensity hand-held hair dryer at 15 cm would give a daily exposure of 140 μT·h. Similarly, carpenters who use power tools for extended periods on a daily basis can be exposed to exceedingly high fields. Once again based on the highest fields associated with power saws (Table 9) at 15 cm for a 2-h daily exposure would give a 200 μT·h exposure.

Magnetic resonance imaging (MRI) also known as nuclear magnetic resonance (NMR) is an imaging technique that exposes the body to a strong static magnetic field, approximately 60 000 times that of the earth’s magnetic field, and to bursts of radio frequencies. The static field aligns hydrogen atoms in the body and the radio frequency absorbed by the atoms is re-emitted to give a signal that generates the image. The magnetic flux density to which technicians are exposed ranges from 0.05 to 28 μT (Table 14).

Patients are exposed to much higher values. Little information is available about the long-term health effects associated with MRI. This technology should be carefully monitored because of the very high fields generated and the increasing use of this technology in diagnosis and research.

5.3. Transportation

The few studies that document magnetic field exposure associated with transportation suggest that exposure can be quite high depending on the mode of travel.

Typical magnetic fields for commuter trains (Table 15) are much higher than for most occupational exposure (Table 12). According to Bennett (1994), magnetic flux densities of 24 μT have been recorded 1 m above the floor and 4 m from the line of an electric commuter train. In the Amtrak train from Washington to New York, the average magnetic field at 25 Hz was 12.6 μT and the maximum field was 64 μT.

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Fig. 4. Personal exposures to magnetic fields measured with exposure meters worn by four workers in different occupations. The plots do not necessarily represent typical EMF exposures for workers in these occupations. (Reprinted with permission from EMF Rapid 1996, *Questions and answers: EMF in the workplace*.)

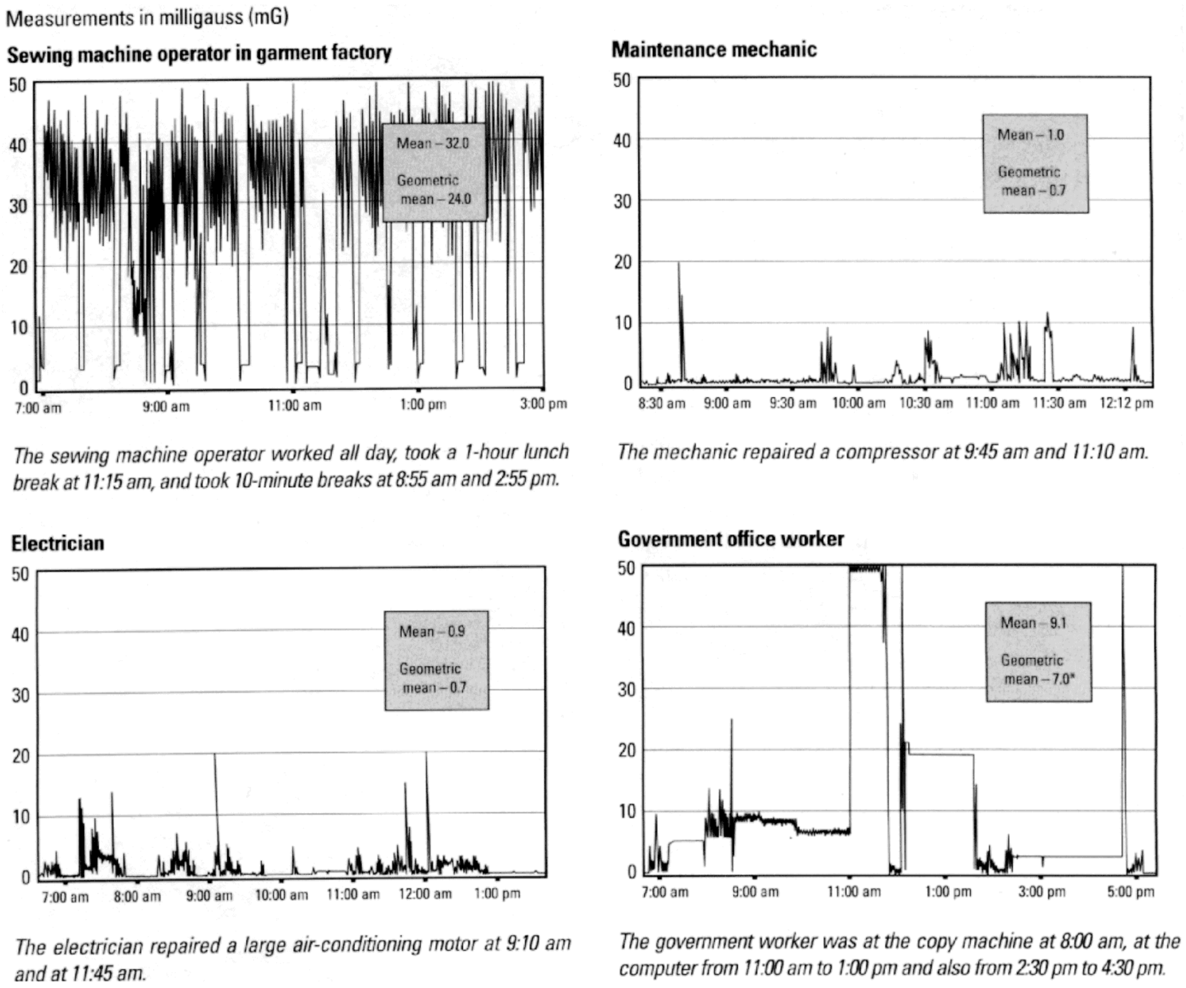

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Table 12. Electrical occupations derived from job titles with time-weighted average (TWA) magnetic field exposures (NIEHS, based on Table 2.4, pp. 61–72).

	Magnetic flux density (μT)		
Occupation	Mean	SD	Code
Textile industry			
Dressmakers and tailors	3.00	0.28	
Worker	1.40	1.47	
Clothing cutter	0.21	0.25	
Utility industry			
Lineman	3.61	10.92	
Electrician	3.01	nd	
Machinest	2.69	nd	
Electrician	1.56	1.63	
Cable splicer	1.50	3.12	
Power plant operator	1.43	2.24	
Relay technician	1.34	2.34	
Technician	1.32	nd	
Electrician	1.11	2.18	
Power plant operator	1.08	nd	
Lineman	1.03	nd	
Substation operator	0.80	1.13	
Welder	0.80	1.08	
Electric generation plant operator	0.79	2.34	
Mechanic	0.77	nd	
Machinist	0.72	1.95	
Lineman	0.65	1.59	
Employee	0.57	1.51	
Painter	0.45	0.45	
Serviceman	0.41	0.69	
Instrument and control technician	0.40	1.12	
Rigger	0.38	0.37	
Technical worker	0.36	0.62	
Engineer	0.33	0.67	
Mechanic	0.30	0.23	
Pipe coverer	0.28	0.44	
Foreman	0.24	0.47	
Mechanic	0.23	0.3	
Transportation industry			
Engineer, railroad	4.03	nd	
Conductor	0.61	nd	
Lineman, railroad	0.59	nd	
Railroad track walker	0.59	nd	
Conductor and motorman	0.57	0.61	
Driver, tram	0.57	0.61	

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Table 12. (*continued*).

	Magnetic flux density (μT)		
Occupation	Mean	SD	Code
Station master and train dispatcher	0.30	nd	
Air traffic controller	0.14	0.23	
Dispatcher	0.14	0.23	
Metal work			
Welder and flame cutters	2.00	4.01	
Electrician	1.56	1.63	
Sheet metal worker	1.34	4.19	
Welder	1.02	nd	
Boilermaker	0.41	1.05	
Factory hand and other unskilled worker	0.36	0.43	
Machine molder	0.18	0.09	
Coil winder	0.15	0.02	
Small equipment			
Repair, household appliance and power tool	0.46	0.52	
Repair, office machines	0.44	0.74	
Repair, radio, TV, and electronic appliances	0.36	0.23	
Repair, AC, heating and refrigeration	0.31	0.27	
Assembler, household appliances	0.15	0.02	
Repair, data processing machine	0.15	0.64	
Electrician, non-utility			
Electrician	1.56	1.63	
Assembler, electrical and electronics	0.57	0.25	
Repair, electrical and electronic equipment	0.51	0.61	
Electrician	0.37	0.32	
Repair, electronic equipment	0.36	0.23	
Technician, electrical engineering	0.35	0.27	
Electrical and electronic engineer	0.33	0.67	
Technician, electronics wireman	0.29	0.39	
Sales, electrical equipment	0.26	0.14	
Electrician	0.25	0.18	
Supervisor, electrician	0.24	0.47	
Technician, engineering	0.2	0.6	
Assembler, electrical machinery	0.15	0.02	
Repair, data processing equipment	0.15	0.64	
Repair, electrical, and electronic equipment	0.14	0.19	
Construction industry			
Carpenter	0.22	0.14	
Heavy equipment operator	0.21	0.16	
Brickmason	0.11	0.05	
Engineering			
Engineer	0.32	0.67	

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Table 12. (*continued*).

Occupation	Magnetic flux density (μT)		Code
	Mean	SD	
Engineer (nonspecified)	0.25	0.41	
Other engineers	0.25	0.41	
Industrial engineer	0.23	0.23	
Operating engineer	0.21	0.16	
Computer services			
Computer programer	0.30	0.55	
Computer programer	0.25	0.28	
Computer system engineer/analyst	0.21	0.41	
Computer operator	0.18	0.24	
Repair, computers and business machines	0.15	0.64	
Computer programer	0.1	0.1	
Machinist			
Tool and die maker	0.28	0.40	
Printing machine operator	0.18	0.09	
Lathe worker	0.17	0.06	
Telecommunication industry			
Lineman	0.43	0.05	
Technician, telephone	0.43	0.10	
Technician	0.35	0.55	
Engineer	0.33	0.67	
Repair	0.25	0.03	
Telephone fitter	0.2	0.13	
Repair and installation, telephone	0.2	0.13	
Repair	0.17	0.02	
Repair and installation, telephone	0.16	0.09	
Assembler	0.15	0.02	
Broadcast equipment operator	0.14	0.23	
Communications equipment operator	0.14	0.23	
Other communications operator	0.14	0.23	
Performer, radio and TV	0.14	0.23	
Announcer, radio	0.14	0.23	
Operator, radio/telegraph	0.14	0.23	
Operator, telegraph operator	0.14	0.23	
Chief communications operator	0.13	0.15	
Foreman	0.13	0.15	
Operator, telephone	0.1	0.01	
Office work			
Mail and message distributing occupations	0.43	0.41	
Receptionist	0.21	0.47	
Billing, posting, and calculating machine operator	0.14	0.13	

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Table 12. (*concluded*).

Occupation	Magnetic flux density (μT) Mean	SD	Code
Accountant	0.15	0.1	
Author and technical writer	0.15	0.17	
General office occupations	0.15	0.18	
Statistician and scientist	0.1	0.05	
Sales			
Sales occupations, retail	0.26	0.14	
Supervisor, sales insurance, real estate	0.2	0.08	
Stock handlers and baggers	0.14	0.08	
Shop assistant	0.11	0.02	
Miscellaneous			
Forestry and logging	2.48	7.70	
Projectionist, motion pictures	0.80	0.68	
Dental hygienist	0.64	1.65	
Groundskeeper and gardener	0.41	0.90	
Traffic, shipping, and receiving clerks	0.36	0.30	
Maintenance man	0.31	0.31	
Precision inspectors	0.29	0.39	
Farmer	0.27	0.54	
Food and beverage preparation	0.22	0.13	
Janitor and cleaner	0.17	0.09	
Teacher	0.15	0.09	
Highway patrolman	0.15	0.09	
Chemist	0.15	0.06	
Medical technologist	0.13	0.19	
Social worker	0.09	0.02	

Note: Very high: 0.66 µT, 95th%; above average: 0.27 µT, 75th%; average: 0.17 µT, 50th%; below average: 0.12 µT, 25th%; TWA = time weight average; sd = standard deviation.

Passengers may not be on these commuter trains for long but workers are exposed to them all day. The MAGLEV (magnetic levitation) electric train produces varying frequencies and magnetic flux densities. Alternating currents in a set of magnets in the guide way change polarity to push/pull the train. The train is accelerated by increasing the ac frequency. Magnetic flux densities of 50 000 μT have been reported in the passenger compartment where people work (Bennett 1994).

Airplanes generate a 400 Hz electromagnetic field. The highest fields are in the cockpit with values above 10 μT near the conduits behind the pilot and co-pilot and near the windshield (heating element). In the passenger part of the airplane, values between 3 to 0.3 μT are more common (unpublished data). Since flights generally last several hours, cumulative exposure can be considerable, especially for the pilot, co-pilot, and stewards. Employees and passengers are also exposed to higher than average cosmic radiation at these altitudes.

Extensive monitoring of automobiles has not been done, to my knowledge. Preliminary monitoring of a few vehicles suggests much lower magnetic fields than those associated with either commuter trains or airplanes (unpublished data). Drivers are exposed to higher magnetic fields in smaller vehicles than

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Table 13. Magnetic flux density averaged over a workday for various occupations (EMF Rapid 1996, p. 35).

	Magnetic flux density (μT)			Code	
Occupation	Median	5th%	95th%	Median	95th%
Garment industry (Finland)					
Sewing machine operator	2.20	1.00	4.00	very high	very high
Other factory workers	0.30	0.10	0.60	above average	above average
Electrical workers (various industries)					
Welders	0.82	0.17	9.60	very high	very high
TV repairers	0.43	0.06	0.86	above average	very high
Construction electricians	0.31	0.16	1.20	above average	very high
Electrical engineers	0.17	0.05	1.20	average	very high
Electric Utilities					
Distribution substation operators	0.72	0.11	3.40	very high	very high
Electricians	0.54	0.08	3.40	above average	very high
Line workers	0.25	0.05	3.50	average	very high
Clerical workers with computers	0.12	0.03	0.63	below average	above average
Workers off the job (home, travel, etc.)	0.09	0.03	0.37	below average	above average
Clerical workers without computers	0.05	0.05	0.16	below average	below average
Telecommunications					
Cable splicers	0.32	0.07	1.50	above average	very high
Central office technicians	0.21	0.05	0.82	average	very high
Install, maintenance, and repair technicians	0.16	0.09	0.31	below average	above average
Employed men (Sweden)					
Retail sales	0.27	0.08	0.44	above average	above average
Machine repair and assembly	0.17	0.03	0.37	average	above average
Teachers in theoretical subjects	0.12	0.04	0.31	below average	above average
Motor vehicle drivers	0.08	0.03	0.19	below average	average
Construction machine operators	0.04	0.02	0.06	below average	below average
Auto transmission manufacturing					
Machinists	0.19	0.06	2.80	average	very high
Assemblers	0.07	0.02	0.49	below average	above average
Hospitals					
X-ray technicians	0.15	0.10	0.22	below average	average
Nurses	0.11	0.05	0.21	below average	average

Note: Code based on NIEHS occupational exposure: very high: TWA 0.66 (μT), 95th%; above average: TWA 0.27 (μT), 75th%; average: TWA 0.17 (μT), 50th%; below average: TWA 0.12 (μT), 25th%.

in larger ones, presumably since they sit closer to the alternator. Air conditioning, heating, and radios all contribute to the ambient magnetic field. Motorbike riders are exposed to high magnetic fields in excess of 3 μT on the seat of the motorbike (unpublished data).

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Table 14. Extremely low frequency magnetic fields at various occupational sites (EMF Rapid 1996, p. 37).

Industry and sources	ELF magnetic flux density (μT)	Other frequencies	Comments
Equipment manufacturing			
Electric resistance heater	600–1400	VLF	
Hand-held grinder	300		Tool exposures measured at operator's chest
Induction heater	1–46	High VLF	
Grinder	11		
Lathe, drill press, etc.	0.1–0.4		
Electrogalvanizing			
Rectification room	100–460	High static field	
Outdoor electric line and substation	10–170		
Aluminum refining			
Rectification room	30–330	High static field	
Aluminum pot rooms	0.34–3	Very high static field	
Steel foundry			
Ladle refinery: electrodes active	17–130	High ULF	
Electrogalvinizing unit	0.2–110	High VLF	
Television broadcasting			
Video tape degausser	16–330		1 foot away
Light control center	1–30		Walk-through survey
Video cameras (studio and microcams)	0.72–2.4	VLF	
Studios and newsrooms	0.2–0.5		

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Table 14. (*concluded*).

Industry and sources	ELF magnetic flux density (μT)	Other frequencies	Comments
Telecommunication			
Switching rooms	0.01–130	Static, ULF–ELF transients	Walk-through survey
Relay switching racks	0.15–3.2	Static, ULF–ELF transients	2-3 inches from relays
Underground phone vault	0.3–0.5		Walk-through survey
Hospitals			
Magnetic resonance imaging (MRI)	0.05–28	Static, VLF, RF	Technician's work location
Intensive care unit	0.01–22	VLF	Nurse's chest
Post-anesthesia care unit	0.01–2.4		
Government offices			
Building power supply	2.5–18		
Desktop cooling fan	100		6 inches away
Other office appliances	1–20		
Power cables in floor	1.5–17		
Desks near power center	1.8–5		
Desk work locations	0.01–0.7		Peaks due to laser printer

Note: Static: direct current, 0 Hz; ULF: ultra-low frequency, <30 Hz; ELF: extremely low frequency, 30–300 Hz; VLF: very low frequency, 300–30 kHz; RF: radio frequency, 30 kHz – 300 MHz.

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Table 15. Typical magnetic fields from commuter trains. Measurements made at 3.5 ft (110 cm) above the floor and include the frequency range of 5 to 2560 Hz (source EPA 1993, in NRC 1997, Table 2.8, p. 35).

	Magnetic flux density (μT)			
Train	Minimum	Average	Maximum	Comments[a]
Amtrack (nonelectric)	0.09	0.64	1.3	
	nd	3.5[a]	26[a]	NY to New Haven (60 Hz)
	nd	12.6[a]	64[a]	Washington to NY (at 25 Hz)
MAGLEV (electric)	0.99	3.06	7.7	50 mT and 700 V/m maximum where people work
Electric Railroad (worst case)	nd	nd	24[a]	1 m above ground and 4 m from line
Boston Subway (electric)	0.02	0.34	1.8	
Washington, D.C. Subway (electric)	0.60	6.02	14.6	

Note: nd: no data.
[a]Source: Bennett 1994.

5.4. Complications with exposure

Although we are beginning to get a clearer picture of the magnetic environment we have created and can now estimate cumulative exposures, there is much we still do not know. It is not clear what attributes of the field are important biologically. Are values above a certain threshold critical; if so, what is that threshold? Are the rapid changes between high and low intensities biologically significant or should we focus on time-weighted cumulative exposure? We have yet to determine the metric of biological significance.

To complicate matters, the electromagnetic environment consists of an electric field as well as a magnetic fields. Although the previous section and much of the literature have focused on magnetic fields, conditions exist where both fields are present (a person standing directly under a power line or someone in contact with an electrical appliance, for example). A changing electric field generates a magnetic field and a changing magnetic field generates an electric current. Therefore, relative motion between external magnetic fields and an individual can generate internal electric currents, so a distinction between the electric and magnetic components is not simple. The biological response is likely to be a function of the fields or currents induced within our bodies rather than the external fields to which we are exposed. This induced internal field/current is difficult to measure and equally difficult to calculate.

More than one frequency can be generated by the power distribution system. While the dominant frequency might be 60 Hz, harmonics (multiples of the original frequency) and subharmonics (fractions of the original frequency) as well as transients (spikes generated by random on and off switching) are produced. The monitoring devices used to measure EMFs over a 24-h period do not necessarily record transients. Some of the studies suggest both frequency and intensity windows, namely biological effects that are frequency and intensity specific (Blackman et al. 1979; Liboff 1985; Dutta et al. 1989). A slightly higher or lower frequency (or intensity) may not necessarily illicit the same biological response. Frey (1994) comments that a good model for biological response may be one based on the radio tuned to a specific modulation.

Not only do the electric and magnetic fields fluctuate at several superimposed frequencies and vary

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in time and space but they also vary in direction. The field to which a person is exposed near a power line depends on whether he is standing (vertical) or lying down (horizontal). Electric field exposure also depends on the degree of grounding, which is influenced by the type of footware.

Biological response may also be influenced by the local magnetic field produced by the earth and this field may be spatially and temporally heterogeneous (Liboff 1985). What is becoming obvious is that the area of research concerned with EMF exposure is immensely complex. It is also of vital importance if we plan to untangle the threads of a vast storehouse of data and if we plan ultimately to understand biological interactions with electromagnetic fields.

6. Biological response to electromagnetic fields

6.1. Cancer

Epidemiological studies of cancer have focused on two primary populations: children in residential settings and adults in occupational settings. The main cancers associated with EMF exposure are leukemias, lymphomas, and central nervous system tumors in children and leukemias, breast cancer, and central nervous system tumors in adults.

Cancer in children

A summary of meta-analyses for childhood cancers is provided in Table 16. The odds ratio (OR) represents the ratio of observed cases to expected cases for a particular form of cancer. The higher the OR the greater is the incidence rate for that cancer in the population under study. An OR of 1 suggests no difference between cases and the reference population. Size of population and proper matching of controls are critical for a valid statistical outcome.

The results in Table 16 indicate that most of the OR are above 1 with only a few studies at or below 1 (hatched) and half of these are for low ($< 0.2\ \mu$T) EMF exposure. Not all OR above 1 are necessarily significant. If the odds ratios above 1 are due entirely to chance, however, the number of studies with OR above and below 1 would be comparable and this is not the case.

Two studies suggest a dose/response relationship (Feychting et al. 1995; Meinert and Michaelis 1996). Odds ratios at and above 0.2 μT (Wertheimer and Leeper 1982; Ahlbom et al. 1993) appear to be critical for childhood cancers. At 0.3 μT and higher, odds ratios above 5 have been reported, which suggests more than a 5-fold increased incidence of these cancers in children (Meinert and Michaelis 1996; Feychting et al. 1995). These values are low compared with other known carcinogens like cigarettes and asbestos but are certainly well above background. One point that must be kept in mind is that exposure to EMF is so “universal and unavoidable that even a very small proven adverse effect of exposure to electric and magnetic fields would need to be considered from a public health perspective: a very small adverse effect on virtually the entire population would mean that many people are affected.” (NRC 1997, p. 196).

The other point that needs to be remembered is that we do not have true controls in the sense of zero exposure to technofields. Zero exposure to technologically generated EMF is no longer possible. Even in remote regions people are increasingly exposed to broadcast frequencies from radio, television, and satellite communication devices. Hence, all of these studies compare higher exposure to lower exposure.

Irrespective of which metric is used (wire codes, distance, measurements, or calculations of exposure), when viewed as a whole (Table 17), the majority of the studies suggest an OR well above 1. Critical distances appear to be approximately 50 m from a power line and critical magnetic flux densities are above 0.15 μT. Daytime spot measurements give the lowest ORs while median night measurements gave the highest. Night-time exposure may be particularly important and may represent a “time-window effect.”

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Recent studies of childhood cancers

Three epidemiological studies were published during the review of this paper that relate to childhood cancers and power lines. Two were Canadian studies (McBride et al. 1999; Green et al. 1999) and one was British (Day et al. 1999). I summarize them here to keep this review as current as possible. Green et al. (1999) conducted a case ($n = 88$) control ($n = 133$) study in Ontario and used different methods to assess EMF exposure, including 48-h personal monitoring, point-in-time measurements, and wire codes. Green et al. found an increased risk of leukemia associated with both point-in-time measurements of the magnetic flux density in the child's home and average magnetic flux density measured by personal monitors . A significant (adjusted) OR of 4.5 was calculated for all leukemias among children up to age 14 exposed to an average magnetic flux density (personal monitoring) at or above 0.14 μT. The OR was lower (3.5) and non-significant for acute lymphoblastic leukemia. For children less than 6 years old the statistically significant OR (unadjusted) was 3.7 for all leukemias and 5.7 for acute lymphoblastic leukemia for the same average magnetic flux density of 0.14 μT. Neither the very high current configuration wire code used by Wertheimer and Leeper nor the high wire code used by Kaune and Savitz showed a significant OR.

In contrast to this study, McBride et al. (1999) reported no significant odds ratios for leukemia among children from five provinces (British Columbia, Alberta, Saskatchewan, Manitoba, and Quebec). McBride's group assessed EMF exposure also using different methods (48-h personal monitoring, 24-h bedroom measurements, and wire codes) in a case-control study consisting of 399 cases and the same number of controls. Although this study was not specifically designed to test risk associated with distance, the authors found that "confounder-adjusted OR" for children living with 100 m or 50 m of a line were elevated but not statistically significant (OR 1.81 for all types of leukemia and OR 1.99 for acute lymphatic leukemia).

One possible source of error in this study is that data from the five provinces were combined for wire codes. We saw in Table 7 that magnetic flux densities can vary enormously for wire codes in different jurisdictions and for that reason should not be combined unless statistical tests show that they are the same within a particular wire code category. This does not explain the lack of relationship with 48-h personal monitoring of magnetic flux density and incidence of leukemia. Clearly this study does not provide support for an increased risk of childhood leukemias with EMF exposure.

Unlike previous childhood epidemiological studies, both Green et al. (1999) and McBride et al. (1999) monitored electric field exposure as well as magnetic flux density. Neither found a significantly higher risk (OR) of leukemia with increasing electric field exposure. The highest electric potential categories were above 11.6 V/m in the Green study and between 25 and 65 V/m in the McBride study.

One key question needs to be answered and that is what metric should be measured? Does a 48-h personal monitoring adequately assess our exposure to electromagnetic fields? Could it be that exposure in these environments to pollutant aerosols is a contributing factor to cancer as suggested by Fews et al. (1999) who found elevated deposition of radon decay products near 400, 275, and 132 kV ac transmission lines?

One of the largest childhood cancer studies associated with exposure to power-frequency magnetic fields was recently published by Day (1999). This was a case-control study covering England, Wales, and Scotland and consisted of 3838 cases and 7629 controls. Despite the large sample size, only 17 individuals (8 cases and 9 controls) or less than 0.4% of the study group were exposed to magnetic flux densities above 0.4 μT. The adjusted odds ratios for acute lymphoblastic leukemia and total leukemias were a non-significant 1.51 and 1.68, respectively. The only statistically significant result was for cancers of the central nervous system for the category between 0.1 and 0.2 μT. Higher magnetic field exposures were non-significant for CNS cancers. According to the author this study provided no support for the hypothesis that power-frequency magnetic fields increase the risk of childhood cancer. However, Day does state that "a scientific question may still remain about the effect of exposures higher than 0.4 μT."

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Table 16. Summary of meta-analyses for childhood cancers (based on Table 4.25,

Meta-analyses	Description[a]
NRPB 1992[b]	Wire codes (HCC vs. LCC)
	Distance from EMF source
	Measured EMF
Ahlbom et al. 1993	Calculated EMF
Washburn et al. 1994[c]	Distance: 50 m boundary
NAS Report 1994[c, d]	Wire codes (HCC vs. LCC): fixed
	Wire codes (HCC vs. LCC): random
	Wire codes and distance <100 m: fixed
	Wire codes and distance <100 m: random
	Spot measurements (≥2 mG): fixed
	Spot measurements (≥2 mG): random
Feychting et al. 1995[e]	Estimated 0.1–0.19 µT
	Estimated >0.2 µT
	Estimated >0.5 µT
Meinert and Michaelis 1996[c, f]	Wire code (HCC vs. LCC)
	Distance: <100 m
	Distance: <50 m
	Distance: <25 m
	EMF measured: >0.1 µT
	EMF measured: >0.2 µT
	EMF measured: >0.3 µT

Note: ■ OR > 1, 95th% Cl ≥ 1; ▦ OR > 1, 95th% Cl < 1; ▨ OR ≤ 1, 95th% Cl ≤ 1.
[a]HCC = high current configuration; LCC = low current configuration.
[b]Wertheirmer and Leeper (1979) study not included.
[c]Wertheirmer and Leeper (1979) study included.
[d]Estimates based on fixed and random effects statistical models.
[e]Reference <0.1 µT (adjusted for age, gender, and country).
[f]Dichotomous cut-points.

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pp. 205–206 in NIEHS 1998).

Odds ratios (95% confidence intervals)							
All cancers	Leukemias	CNS tumors	Lymphomas	All	Leu	CNS	Lym
1.53 (1.04–2.25)	1.39 (1.08–1.78)	2.04 (1.11–3.76)					
1.11 (0.71–1.73)	1.31 (0.72–2.21)	1.09 (0.50–2.37)					
1.82 (1.09–3.04)	1.16 (0.65–2.08)	1.85 (0.91–3.77)					
1.3 (0.9–2.1)	2.1 (1.1–1.41)	1.5 (0.7–3.2)	1.0 (0.3–3.7)				
	1.49 (1.11–2.00)	1.89 (1.34–2.67)	1.58 (0.91–2.76)				
	1.48 (1.18–1.85)						
	1.52 (1.08–2.14)						
	1.36 (1.13–1.63)						
	1.38 (1.08–1.76)						
	0.92 (0.57–1.49)						
	0.89 (0.51–1.57)						
1.4 (0.6–2.9)	2.0 (0.7–5.3)	1.1 (0.3–3.6)	0.7 (0.1–5.6)				
1.5 (0.9–2.7)	2.0 (1.0–4.1)	0.8 (0.3–2.4)	2.1 (0.8–5.5)				
3.5 (1.7–7.3)	5.1 (2.1–12.6)	2.3 (0.6–8.0)	3.3 (0.7–15)				
1.37 (0.94–2.00)	1.66 (1.11–2.49)	1.50 (0.69–3.26)	1.32 (0.52–3.37)				
1.09 (0.89–1.35)	1.13 (0.79–1.62)						
1.10 (0.86–1.40)	1.31 (0.92–1.87)	1.53 (0.19–12.0)					
1.42 (0.88–2.29)	1.85 (0.98–3.49)						
0.97 (0.82–1.15)	1.55 (0.88–2.73)	0.89 (0.39–2.05)	2.18 (0.51–9.34)				
1.23 (0.96–1.57)	1.89 (1.10–3.26)	1.30 (0.78–2.19)	2.21 (0.72–6.80)				
1.62 (1.10–2.39)	1.27 (0.28–5.76)	1.89 (0.80–4.43)	1.69 (0.43–6.59)				

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Cancer in adults

For adults, the link between EMF exposure and leukemia (Table 18), brain tumors (Table 19), and breast cancer (Table 20) is also convincing when viewed as a whole. Two forms of leukemia seem to predominate: acute myeloid leukemia (AML) and chronic lymphocytic leukemia (CLL). As with childhood cancers there is some evidence for a dose/response relationship (Table 18) although it is very difficult to measure dose in an occupational setting and estimates can provide only ball-park figures. For this reason it is difficult to provide a threshold value, if indeed one exists, based on the information available.

Among the cancers, the one with the highest OR is breast cancer in men. Several studies in Table 20 indicate a relative risk (RR) above 4 for men while the highest value for women is 2. This form of cancer is rare among men and the presence of one or two cases is likely to result in a high risk estimate. The lower OR of 2 for women should not be taken lightly since as many as 5 000 women die from breast cancer each year in Canada and as many as 44 000 die in the United States (WHO 1998).

Another concern related to cancer is parental exposure and pre-natal exposure to electromagnetic fields with subsequent tumor development in offspring. Once again, there is some evidence that relative risk (RR) or the standardized incidence ratio (SIR)[3] is elevated (Tables 21 and 22) but, for these studies, sample size is low and the 95% confidence interval is broad. Only two of the seven studies in Table 21 reported a significant elevated relative risk for central nervous system tumors in offspring of EMF-exposed parents. This topic is discussed in greater detail in the section on Reproduction.

Mechanisms

The fact that different cancers are associated with EMF exposure and that not all studies show a higher incidence (or odds ratio) for a particular form of cancer is not an inconsistency if EMFs promote rather than initiate cancer.

Animal studies confirm this perspective. Exposing laboratory animals to EMFs does not result in cancer unless they already have cancerous cells in their body. Often strains prone to develop a specific type of cancer are selected as the test organism or well-known cancer initiators such as MNU (*N*-methyl-*N*-nitrosourea) or DMBA (7,12-dimethylbenz[*a*] anthracene) are used prior to EMF exposure in laboratory studies.

Some of the most convincing studies deal with mammary cancer in rats (Table 23). Several interesting observations can be made when the data are viewed together. The data in Table 23 have been ranked according to the magnetic flux density used in the experiment. At higher magnetic flux densities ($\geq$250 μT) there is some evidence of a beneficial effect of EMF exposure. In experiments that tested a magnetic flux density of 100 μT or less, the tumor promoting effects of EMFs (based on incidence rates, number of tumors per animal, tumor size, and latency period) become more evident. This supports the concept that higher intensities may not necessarily be more harmful and that the classical toxicological model based on dose-response may not be an appropriate model for EMF exposure.

Of the metrics used to quantify tumor promotion, increases in the incidence rate and decreases in the latency period seem to be most strongly associated with EMF exposure below 100 μT (Table 24). Both of these suggest that EMFs compromise the immune system or promote cell division, resulting in a more aggressive form of cancer.

Studies show that cell proliferation is enhanced in the presence of an alternating EMF (Katsir et al. 1998). This is also supported by early studies on the effects of varying geomagnetic fields on cell mitosis (for human skin carcinoma) (Dubrov 1978). The rate of mitosis seems to be enhanced in a varying electromagnetic field. Thus, the apparent inconsistency that links EMFs to healing and cancer

[3] Standardized incidence ratio (SIR), standardized mortality ratio (SMR), relative risk (RR), and odds ratio (OR) are three ways of measuring the "risk" of association in different types of epidemiological studies.

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Table 17. Residential electromagnetic field exposure and childhood leukemia. Based on Table A5-4 in NRC 1997 and Table 4.21 in NIEHS 1998.

Cited in: NRC	Cited in: NIEHS	Reference (location)	Category[a]	Associated magnetic flux density (µT)[a,b]	Crude OR or RR[c]	95% CI	Cases	Controls
Wire code								
Yes	Yes	Wertheimer and Leeper 1979	HCC vs. LCC: at death	HCC = 0.25 (median)	3.0	1.8–5.0	145	154
		(Denver, Colo., U.S.A.)	HCC vs. LCC: at birth	LCC < 0.05 (median)	2.3	1.3–3.9	136	136
Yes	No	Fulton et al. 1980	VH	VH = 0.18 (mean)	1.0	0.6–1.8	47.5	56.3
		(Rhode Island, N.Y., U.S.A.)	OH	OH = 0.096 (mean)	1.2	0.7–2.1	55.4	56.3
			OL	OL = 0.065 (mean)	1.1	0.6–1.9	49.5	56.3
			Reference = VL	VL = 0.044 (mean)			45.5	56.3
Yes	Yes	Savitz et al. 1988	VH vs. VL	VH = 0.216; VL = 0.03	2.8	0.9–8.0	35	96
		(Denver, Colo., U.S.A.)	OH vs. L	OH = 0.09; OL = 0.05	1.5	0.9–2.6	97	259
Yes	Yes	London et al. 1991	VH	VH = 0.107 (median)	2.2	1.1–4.3	42	24
		(Los Angeles, Calif., U.S.A.)	OH	OH = 0.066 (median)	1.4	0.8–2.6	80	68
			OL	OL = 0.058 (median)	1.0	0.5–1.7	58	75
			Reference = VL	VL = 0.043 (median)			20	27
No	Yes	Linet et al. 1997	VH		0.9	0.5–1.6	408 (matched cases)	
	New	(location not given)	OH		1.0	0.7–1.5		
		Acute Lymphoblastic Leukemia	OL		1.1	0.7–1.5		
		(ALL)	UG + VL = reference	Reference for wire code	ALL			
Distance								
Yes	No	Feychting and Ahlbom 1993	To power line	<51 m = 0.138 (mean)	2.9	1.0–7.3	6	34
		(Sweden)	To power line	51–100 m = 0.065 (mean)	1.1	0.4–2.7	6	89
			Reference	≥101 m = 0.044 (mean)			26	431
Yes	No	Coleman et al. 1989	To substation	0–24 m = 0.18 (mean)	1.6	0.3–8.4	3	3
		(SE London, U.K.)	To substation	25–49 m = 0.096 (mean)	1.5	0.6–3.6	11	12
			To substation	50–99 m = 0.065 (mean)	0.7	0.4–1.4	22	48
			Reference	>100 m = 0.044 (mean)			48	78
Measured								
Yes	Yes	Savitz et al. 1988	At low power	0.2	1.9	0.7–5.6	36	207
		(Denver, Colo., U.S.A.)	At high power	0.2	1.4	0.6–3.5	37	204
Yes	No	Tomenius 1986	Total residence	≥0.3	0.3	0.1–1.1	4	10
		(Stockholm, Sweden)	Reference	<0.3			239	202
Yes	No	London et al. 1991	24-h	≥0.268	1.5	0.7–3.3	20	11
		(Los Angeles, Calif., U.S.A.)	24-h	0.119–0.267	0.9	0.5–1.7	24	22
			24-h	0.068–0.124	0.7	0.4–1.2	35	42

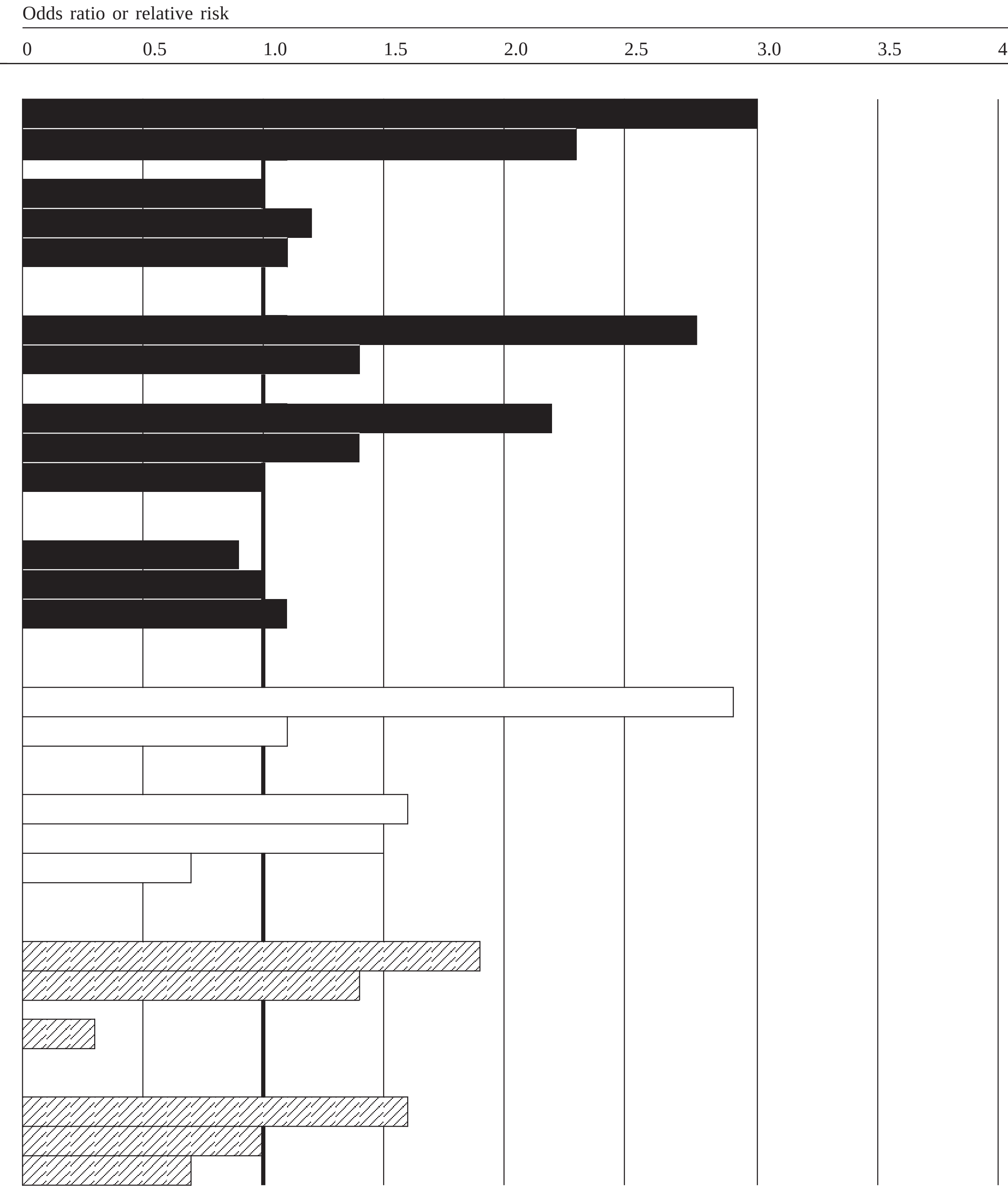


Table 17. (*continued*).

Cited in NRC	Cited in NIEHS	Reference (location)	Category[a]	Associated magnetic flux density (µT)[a,b]	Crude OR or RR[c]	95% CI	Cases	Controls
			Reference for 24-h	≤0.067			85	69
No	Yes	Linet et al. 1997	24-h	0.4–0.499	6.4	1.3–32	463 matched pairs	
	New	(location not given)	24-h	0.3–0.399	1.5	0.6–3.5		
		Acute Lymphoblastic Leukemia	24-h	0.2–0.299	1.3	0.7–2.5		
		(ALL)	24-h	0.1–0.199	1.2	0.8–1.7		
		Matched analysis	24-h	0.065–0.099	1.0	0.7–1.4		
			Reference	<0.065				
No	Yes	Michaelis et al. 1998	Median at night	≥0.2	3.9	0.9–17		
	New	(Germany)	Median measurement	≥0.2	3.2	0.7–15		
			Mean measurement	≥0.2	1.5	0.4–5.5		
			Control	<0.2				
No	Yes	Michaelis et al. 1997	Median at night	≥0.2	3.8	1.2–12	129	2 controls
	New	(Lower Saxony, Germany)	Median measurement	≥0.2	2.3	0.8–6.7		per case
			Reference	<0.2				
Yes	No	London et al. 1991	Spot	>0.125	1.2	0.5–2.8	16	11
		(Los Angeles, California, USA)	Spot	0.068–0.124	1.4	0.7–2.9	23	14
			Spot	0.032–0.067	1.0	0.6–1.9	34	28
			Reference	≤0.031			67	56
Estimated								
Yes	No	Feychting and Ahlbom 1993	Spot	>0.2	0.6	0.2–1.8	4	70
		(Sweden)	Spot	0.1–0.19	0.2	0.0–0.9	1	67
			Reference	<0.1			19	207
Yes	No	Feychting and Ahlbom 1993	Estimated	≥0.3	3.8	1.4–9.3	7	32
		(Sweden)	Estimated	≥0.2	2.7	1.0–6.3	7	46
			Estimated	0.1–0.29	1.5	0.4–4.2	4	47
			Estimated	0.1–0.19	2.1	0.6–6.1	4	33
			Reference	<0.09			27	475
Yes	Yes	Olsen et al. 1993	Estimated	≥0.4	6.0	0.8–44	3	1
		(Denmark)	Estimated	≥0.25	2.5	0.3–6.7	5	4
		Adjusted OR used	Estimated	≥0.1	1.0	0.3–3.3	4	8
			Estimated	0.1–0.39	0.3	0.0–2.0	1	7
			Estimated	0.1–0.24	0.5	0.1–4.3	1	4
			Reference	<0.1			829	1658

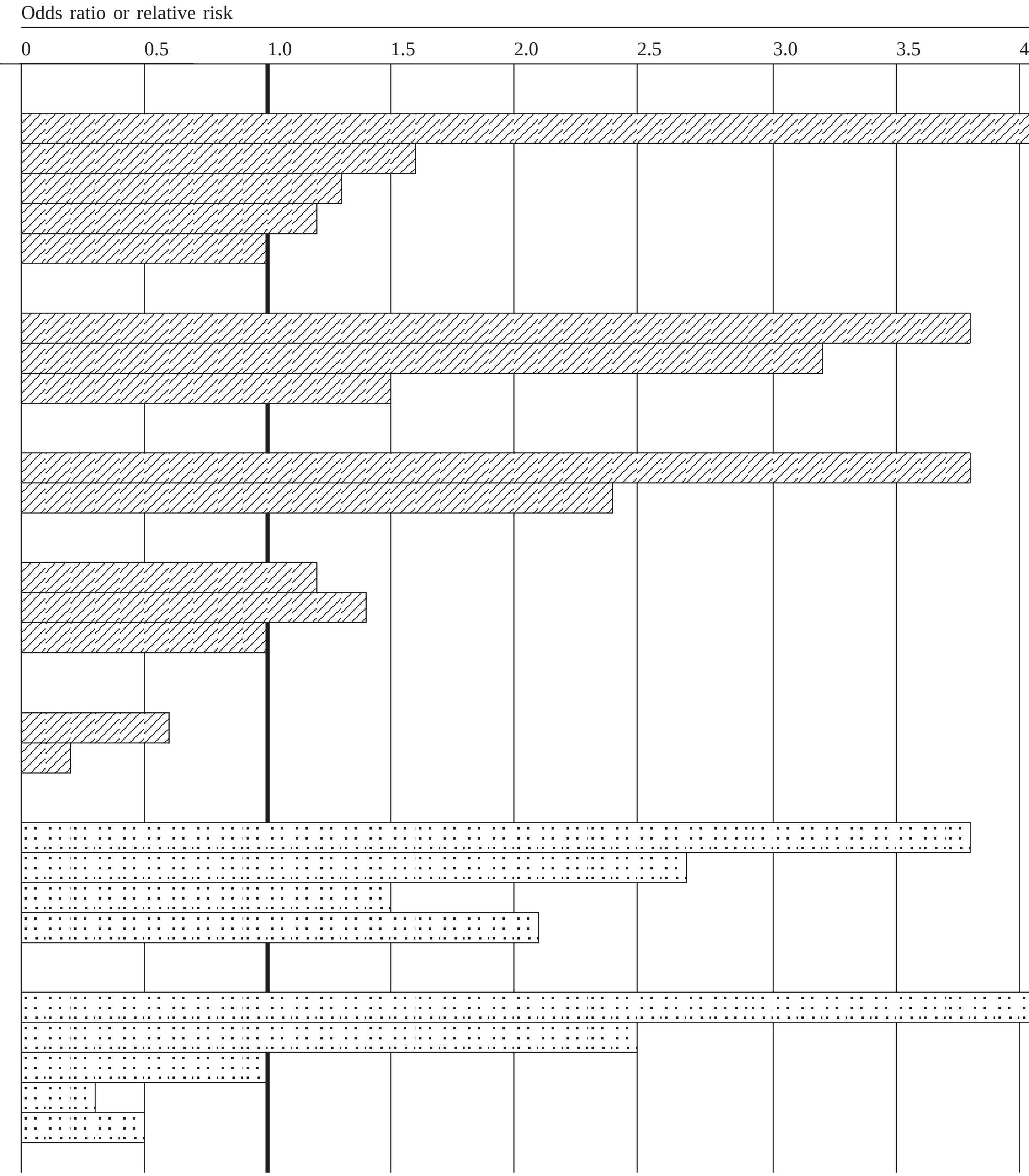
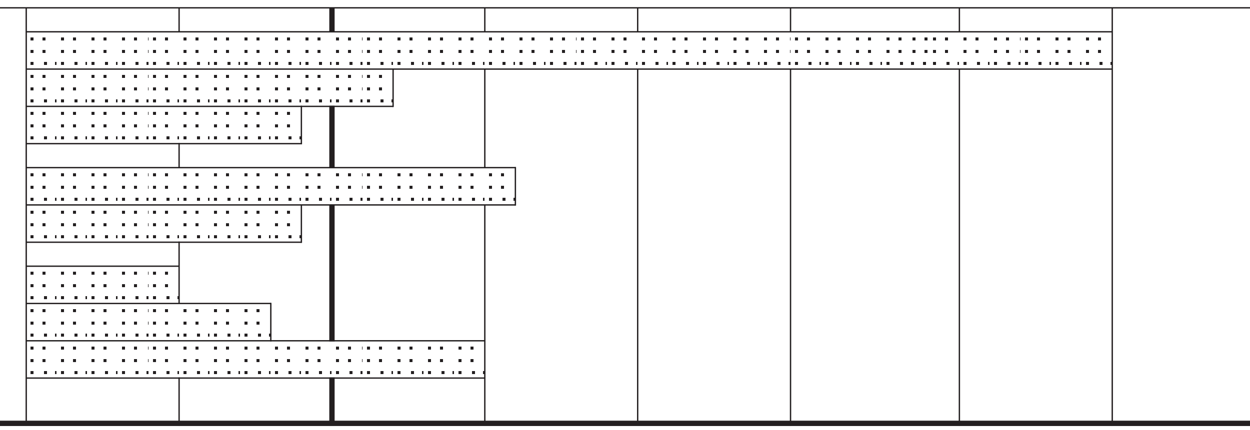


Table 17. (*concluded*).

Cited in NRC	Cited in NIEHS	Reference (location)	Category[a]	Associated magnetic flux density (μT)[a,b]	Crude OR or RR[c]	95% CI	Odds ratio or relative risk (0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0)	Cases	Controls
Yes	Yes	Verkasalo et al. 1993, 1994	10-yr cumm. exposure	≥1.0	3.5	0.7–10		144	cohort size
		(Finland)	10-yr cumm. exposure	≥0.40	1.2	0.3–3.6		cases	68 300 boys
			10-yr cumm. exposure	0.01–0.39	0.9	0.6–1.3		identified	66 500 girls
Yes	Yes	Verkasalo et al. 1993, 1994	Average exposure	≥0.2	1.6	0.3–4.5		3	1.93 expected
		(Finland)	Average exposure	>0.01–0.19	0.9	0.6–1.3		32	36.1 expected
No	Yes	Tynes and Haldorson 1997	Closest to diagnosis	≥0.2	0.5	0.1–2.2		500 max	2004 max
	New	(Norway)	Closest to diagnosis	≥0.14	0.8	0.3–2.4		5 controls/case selected	
			Closest to diagnosis	0.05–0.13	1.5	0.7–3.3			
			Reference	<0.05					



Note: wire code; distance; measured; estimated.

[a]Wire codes: VH = very high; OH = ordinary high; OL = ordinary low; VL = very low; HCC = high current configuration; LCC = low current configuration; UG = underground

[b]Magnetic fields for wire codes and distance categories are based on data in Appendix B, NRC 1997.

[c]OR = odds ratio; RR = relative risk; cumm. = cummulative; expected = based on population at large.

Table 18. Epidemiological studies of leukemia with full-shift measurements of magnetic fields (Table 4.11, pp. 147–150, NIEHS 1998).

Reference, country, study type, and sample size	Description[a]	Exposure (μT unless otherwise noted)	Leukemia Cases	Leukemia OR[b]	Leukemia 95% CI[c]		Acute myeloid leukemia Cases	Acute myeloid leukemia OR[b]	Acute myeloid leukemia 95% CI	Chronic lymphocytic leukemia Cases	Chronic lymphocytic leukemia OR[b]	Chronic lymphocytic leukemia 95% CI	Leu	AML	CLL
Matanoski et al. 1993	CE: TWA > median		35	2.5	0.7–8.6	ns									
USA, AT&T employees	Peak > median (w/all switches)		35	1.6	0.5–4.9	ns									
3 controls/case	Peak > median (w/old switches)		35	2.6	0.8–8.6	[c]									
Sahl et al. 1993	Total CE: TWA	25 μT-year	13	1.1	0.8–1.5										
Cal. Edison Co. utility workers	Total CE: median	3.5 μT-year	10	1.0	0.75–1.4										
10 controls/case	Total CE: 2–12 years before death: median	3.5 μT-year	nd	0.6	0.32–1.2										
Miller et al. 1996	CE TWA: E-field: nd	3.2–7 μT-year	16	1.7	0.58–4.8										
Canada, Ontario Hydro Cohort utility workers		≥7.1 μT-year	24	1.6	0.47–5.2										
1484 cancer cases, 50 leukemia cases															
	CE TWA: E-field: 172–344 V/m-year	3.2–7 μT-year	2	1.2	0.10–15										
		≥7.1 μT-year	6	7.8	1.1–58										
	CE TWA: E-field: E-field > 345 V/m-year	3.2–7 μT-year	8	11	1.5–84										
		≥7.1 μT-year	17	11	1.3–97										
Johansen and Olsen 1998	TWA: low exposure (men only)	0.1–0.29	16	1.0	ns										
Denmark, utility worker cohort,	TWA: medium exposure (men only)	0.3–0.99	16	0.9	ns										
total 32 006	TWA: high exposure (men only)	>1.0	12	1.1	ns										
Kheifet et al. 1997	Measured: 50th–75th%	Low		1.2	0.94–1.6										
Meta-analysis of 38 studies	Measured: 75th–90th%	Medium		1.4	1.1–1.8										
EMF exposed workers	Measured: >90th%	High		1.3	1.0–1.7										
	Broad definition: high EMF exposure or electrical occupations						18	1.4	1.2–1.7	12	1.6	1.1–2.2			
London et al. 1994	TWA: highest category	≥0.81	30	1.4	1.0–2.0		10	2.3	1.4–3.8	4	0.8	0.4–1.5		CML	
LA County, electrical workers							For chronic myeloid leukemia								
Case-control															
Floederus et al. 1993	TWA: 2nd quartile	0.16–0.19					24	1.0	0.5–1.8	17	1.1	0.5–2.3			
Sweden	TWA: 3rd quartile	0.2–0.28					18	0.8	0.4–1.6	33	2.2	1.1–4.3			

Table 18. (*concluded*).

Reference, country, study type, and sample size	Description[a]	Exposure (µT unless otherwise noted)	Leukemia			Acute myeloid leukemia			Chronic lymphocytic leukemia					
			Cases	OR[b]	95% CI[c]	Cases	OR[b]	95% CI	Cases	OR[b]	95% CI	Leu	AML	CLL
Case = 250, control = 1121	TWA: 4th quartile	≥0.29				23	1.0	0.6–1.9	41	3.0	1.6–5.8			
	TWA: >90th percentile	≥0.41				8	0.9	0.4–2.1	22	3.7	1.8–7.7			
Theriault et al. 1994	CE TWA: >median	≥3.1 µT-year				25	3.2	1.2–8.3	24	1.5	0.5–4.4			
Canada and France, utility workers	CE TWA: >90th percentile	≥16 µT-year				4	2.7	0.5–15	6	1.7	0.44–6.7			
4151 cases, 6106 controls														
Savitz and Loomis 1995	CE TWA: highest category	≥4.3 µT-year for AML				5	1.6	0.51–5.1	5	0.55	0.17–1.8			
USA, electric utility workers case-control	CE TWA: highest category	≥2.0 µT-year for CLL												
Feychting et al. 1997	TWA: occupational exp only	<0.20				26	1.7	0.9–3.2	37	1.2	0.7–1.9			
Sweden	TWA: occupational exp only	≥0.20				14	1.8	0.9–3.8	28	1.7	1.0–2.9			
Case-control														
	TWA: occup exp > 2.0 µT: resid exp low	<0.2				11	1.5	0.6–3.6	26	1.5	0.8–2.7			
	TWA: occup exp > 2.0 µT: resid exp high	≥0.20				3	6.3	1.5–26	2	2.1	0.4–10			

Note: OR > 1, 95% Cl ≥ 1; OR > 1, 95% Cl < 1; OR ≤ 1, 95% Cl ≤ 1.
[a]TWA: time-weighted-average; CE: cummulative exposure
[b]OR: odds ratio
[c]$p< 0.05$, ns = not significant
[d]NST = nervous system tumors (includes brain cancer)

is resolved, if the underlying mechanism accelerates cell division, since the growth of cancerous cells as well as healthy cells involved in the healing process can be stimulated.

But changes in the rate of mitosis provides only part of the picture; melatonin provides another. Melatonin plays many roles in the body. One is the regulation of estrogen levels. When melatonin levels are low, estrogen levels are high, and high levels of estrogen stimulate estrogen-sensitive breast cancer (Stevens 1987*a*,*b*). This appears to be true for endogenous estrogen (estrogen produced by the body) and for exogenous estrogen (estrogen supplements) taken by post-menopausal women for example.

Melatonin has several cycles in the body. It has a diurnal cycle with night-time maxima. It has a seasonal cycle with winter maxima. Both of these may be linked to light exposure. Night-time melatonin levels also decrease as people age. The production of melatonin is partly controlled by visible light. Even short periods of light exposure in the evening can decrease night-time melatonin levels while similar exposure earlier in the day has no effect. Electromagnetic frequencies, other than those of visible light, can also influence melatonin synthesis (Wilson et al. 1990).

In animal studies, there is a clear connection among melatonin, mammary cancer, and exposure to EMFs (at visible light and at extremely low frequencies) (Wilson et al. 1990). In humans, the link between light and melatonin has been firmly established and the disruptions of the normal daily cycles of melatonin synthesis are a risk factor for human breast cancer (Stevens 1987*a*,*b*).

Although we know that light affects melatonin, the question remains, “Can electromagnetic fields at power line frequencies and at intensities commonly found in residential or occupational settings affect melatonin production in humans?” This critical question has now been answered. Liburdy et al. (1993) reported a threshold for night-time melatonin production between 0.1 and 1.2 μT. These magnetic flux densities can be found in both residential and occupational settings (see section on Exposure). As with light, timing of exposure may be critical. So exposure to power line frequency EMF at intensities found in the home can reduce night-time melatonin production in humans.

With lower melatonin, estrogen levels increase, which in turn stimulates estrogen-responsive breast cancer. Breast cancer in men and women have been linked to EMF exposure, as shown in Table 21. The EMF – melatonin – estrogen – breast cancer connection is supported by many different types of studies and is one of the more probable mechanisms implicated in EMF exposure. Liburdy et al. (1993) report that normal physiological concentrations of melatonin can decrease the growth rate of MCF-7 cells (human estrogen-responsive breast cancer cells). Melatonin may play a role in other forms of cancer as well since it is a powerful antioxidant that inhibits the proliferation of cancerous cells (Reiter et al. 1995).

Similar results have been obtained for tamoxifen, a strong anti-cancer drug. The action of tamoxifen is blocked at very low magnetic flux densities of 1.2 μT for breast cancer (Harland and Liburdy 1997; Harland et al. 1998). Results have been replicated and extended to other cell lines including human glioma cells (Afzal and Liburdy 1998). The significance of this is that exposure to high electromagnetic fields may block the potential of the drug and thus reduce the effectiveness of chemotherapy for cancer treatment.

The evidence at ambient intensities is mounting to support at least two plausible mechanisms involved in cancer promotion — increased rate of cell division and the role of melatonin in estrogen regulation and as an antioxidant.

6.2. Reproduction

Adverse pregnancy outcomes, including miscarriages, still births, congenital deformities, and illness at birth, have been associated with maternal occupational exposure to electromagnetic fields (Goldhaber et al. 1988) as well as residential use of electric blankets, heated waterbeds, and conductive heating elements in bedroom ceilings (Wertheimer and Leeper 1986, 1989; Hatch et al. 1998). The development of childhood cancers (particularly brain tumors) and congenital deformities have been linked with paternal EMF exposure in occupational settings (Nordstrom et al. 1983; Wilkins and Koutras 1988; Johnson and Spitz 1989; Tornqvist 1998).

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Table 19. Epidemiological studies of brain cancer with full-shift measurements of magnetic fields (from

Reference Country and study type	Description[a]	Exposure μT (unless otherwise noted)
Harrington et al. 1997	CE TWA: highest category	≥ 6.0 μT-year
Central Electricity Generating Board, England and Wales	0–5 yr before diagnosis: highest category	≥ 6.0 μT-year
112 brain cancer deaths, 654 controls, pop'n 84 018		
Sahl et al. 1993	Total CE: TWA	25 μT-year
California Edison Co. utility workers	Total CE: median	3.5 μT-year
32 brain cancer cases, 10 control/case	Total CE: 2–12 yr before death: median	3.5 μT-year
Floederus et al. 1993	TWA: 2nd quartile	0.16–0.19 μT
Sweden	TWA: 3rd quartile	0.2–0.28 μT
346 brain cancer cases, 1121 controls	TWA: 4th quartile	≥ 0.29
	TWA: > 90th percentile	≥ 0.41
Savitz and Loomis 1995	2–10 year window: highest category	≥ 0.7 μT-yr
USA, electric utility workers	CE TWA: highest category	≥ 4.3 μT-year
cohort of 138 905 men with 144 NST deathsd		
Theriault et al. 1994	CE TWA: > median	≥ 3.1 μT-year
Canada and France, utility workers	CE TWA: > 90th percentile	≥ 16 μT-year
250 brain cancer cases, 6106 controls		
Lin et al. 1985	A: definite EM exposure	
Maryland, USA, occupational exposure (white males)	B: probable EM exposure	
951 cases of primary brain tumor deaths	C: possible EMf exposure	
1969–1982; note: astrocytoma includes gliomas	D: no EM exposusre	
Johansen and Olsen 1998	TWA: low exposure (men)	0.1–0.29
Denmark, male and female utility workers	TWA: medium exposure (men)	0.3–0.99
cohort; 46 284 population size	TWA: high exposure (men)	≥ 1.0
	TWA: low exposure (women)	0.1–0.29
	TWA: medium exposure (women)	0.3–0.99
	TWA: high exposure (women)	≥ 1.0
Feychting et al. 1997	TWA: occupational exp only	0.13–0.19
Sweden, occupational and residential exposure	TWA: occupational exp only	≥ 0.20
case-control, 223 CNS tumors		
population size 400 000	TWA: occup exp > 2.0 μT: resid exp low	< 0.2
	TWA: occup exp > 2.0 μT: resid exp high	≥ 0.20

Note: OR > 1, 95% Cl ≥ 1; OR > 1, 95% Cl < 1; OR ≤ 1, 95% Cl ≤ 1.
[a]TWA: time-weighted-average; CE: cummulative exposure
[b]OR: odds ratio
[c]$p < 0.05$, ns = not significant
[d]NST = nervous system tumors (includes brain cancer)

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NIEHS, Table 4.12, pp. 151–153) plus earlier study by Lin et al. 1985.

Brain tumor			Astrocytoma			Other as specified						
Cases	OR[b]	95% CI	Cases	OR[b]	95% CI	Cases	OR[b]	95% CI[c]	Brain	Ast	Other	Type
27	0.97	0.53–1.8										
11	0.59	0.25–1.4										
4	0.81	0.48–1.4										
7	1.0	0.62–1.5										
nd	1.1	0.62–2.0										
59	1.0	0.7–1.6	48	1.3	0.8–2.0							
72	1.5	1.0–2.2	57	1.7	1.1–2.7							
74	1.4	0.9–2.1	52	5.0	1.0–2.4							
24	1.2	0.7–2.1	14	1.1	0.5–2.1							
43	2.6	1.4–4.9										
16	2.3	1.6–4.6	5	1.6	0.51–5.1	5	0.55	0.17–1.8				
48	1.5	0.85–2.8	12	0.97	0.34–2.8	19	2.3	0.79–6.7				Benign tumor
12	2.0	0.76–5.0	5	12	1.1–140	4	1.6	0.35–7.6				
Malignant												
			27	2.15	1.1–4.06	15	1.54	0.68–3.38				
			21	1.95	0.94–3.91	19	1.30	0.60–2.78				
			128	1.44	1.06–1.95	87	0.84	0.68–1.31				
			323	1.00		286	1.00					
						17	0.9	ns				CNS, men
						13	0.7	ns				
						8	0.7	ns				
						3	3.3	ns				CNS, women
						0						
						4	1.4	ns				
						79	1.2	0.8–1.7				CNS
						43	1.2	0.8–1.9				
						40	1.2	0.7–1.9				
						3	1.3	0.3–4.8				

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Table 20. Epidemiological studies of breast cancer with full-shift measurements of magnetic fields (from NIEHS 1998, Table 4.13–4.15, pp. 154–157).

Reference			Male			Female				
			Breast tumor			Breast tumor				
Country	Description	Exposure (μT)	Cases	RR[a]	95% CI	Cases	RR[a]	95% CI	M	F
Demers et al. 1991	All subjects:									
U.S.A.	Welders		4	0.8	0.2–3.1					
	Electric utility trades		13	6.0	1.7–21					
	All electrical occupations		33	1.8	1.0–3.7					
	Exposed before age 30 and for >30 years:									
	Welders		3	4.3	0.4–43					
	Electric utility trades		11	7.4	1.6–34					
	All electrical occupations		22	3.3	1.5–7.3					
Matanoski et al. 1991	Telephone company, line jobs		2	6.5	0.79–24					
New York State, U.S.A.	Central office technicians	Mean = 0.25 μT								
Tynes et al. 1992	Electrical occupations		170	2.1	1.1–3.6					
Norway	Electric transport work		4	4.0	1.1–10					
	Age at death less than 65:									
Loomis 1992	All electrical occupations		3	2.2	0.6–7.8					
U.S.A. (24 states)	Telephone workers		1	9.0	0.9–89					
Floderus et al. 1994	Conductors		1	2.7	0.4–20					
Sweden	Railway workers		4	4.3	1.6–12					
	Engine drivers		2	8.3	2.0–34					
Rosenbaum et al. 1994	Job exposure to EMF		6	0.6	0.2–1.6					
U.S.A. (N.Y. State and western counties)										
Feychting et al. 1997	All subjects: quartile 2	0.16–0.19	17	1.2	0.6–2.7					
Sweden	All subjects: quartile 3	0.20–0.28	17	1.3	0.6–2.8					
Case-control	All subjects: quartile 4	>0.29	11	0.7	0.3–1.9					
	All subjects: 90th percentile	>0.41	4	0.7	0.2–2.3					

Table 20. (*concluded*).

Reference			Male			Female				
			Breast tumor			Breast tumor				
Country	Description	Exposure (μT)	Cases	RR[a]	95% CI	Cases	RR[a]	95% CI	M	F
	≤60 years old: quartile 2	0.16–0.19	9	2.9	0.7–11					
	≤60 years old: quartile 3	0.20–0.28	8	2.5	0.6–9.5					
	≤60 years old: quartile 4	>0.29	5	0.9	0.2–4.5					
	≤60 years old: 90th percentile	>0.41	3	1.5	0.3–8.3					
Guenel et al. 1993	Jobs with intermittent exposure		23	1.2	0.77–1.8	1526	0.96	0.91–1.0		
Denmark	Jobs with continuous exposure		2	1.5	0.16–4.9	55	0.88	0.48–1.2		
Loomis et al. 1994	15 electrical occupations:					68	1.4	1.0–1.8		
U.S.A. (24 states)	Telephone installers, repairers, and line workers[c]					15	2.17	1.17–4.02		
	Electrical engineers[b]					16	1.73	0.92–3.25		
	Electrical technicians[b]					23	1.28	0.79–2.07		
	Jobs with potential exposure:									
	Computer programmer					26	1.1	0.7–1.7		
	Telephone operator					328	0.96	0.84–1.1		
	Data entry keyer					77	0.75	0.42–1.3		
Cantor et al. 1995	White women: medium exposure					1746	1.1	1.0–1.2		
U.S.A. (24 states)	White women: high exposure					123	0.97	0.8–1.2		
	Black women: medium exposure					273	1.3	1.1–1.5		
	Black women: high exposure					20	1.2	0.7–2.1		
Coogan et al. 1996	High exposure jobs: all women					6851	1.4	0.99–2.1		
U.S.A. (4 states)	High exposure jobs: premenopausal women					1424	2.0	1.0–3.8		
	High exposure jobs: postmenopausal women					5163	1.3	0.82–2.2		

Note: OR > 1, 95% CI ≥ 1; OR >1, 95% CI < 1; OR ≤ 1, 95% CI ≤ 1.
[a]RR: relative risk.
[b]These electrical occupations were not included in the NIEHS tables 4.13–4.15.

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Table 21. Central nervous system tumors in offspring of EMF-exposed parents (from NIEHS, Table 4.17, pp. 159–160).

Reference		Nervous system tumors					
Country	Description	Cases	RR	95% CI	*p*	NST	Type
Spitz and Johnson 1985	Narrow definition of EMF exposure	13	2.1	0.9–4.8			Neuroblastoma
Texas, U.S.A.	Broad definition of EMF exposure	17	2.1	1.1–4.4			
Case-control	Electronics workers only	6	12.0	1.4–99			
Wilkins and Koutras (1988)[a]	Construction		2.3	1.3–4.1	0.004		Malignant neoplasm of brain
Ohio-born children, U.S.A.	Metal work		1.8	1.1–2.9	0.02		
Mortality-based case-control	Machinery		1.7	1.1–2.7	0.028		
	Transporation		1.6	1.0–2.4	0.046		
	Welders, cutters	11	2.7	0.9–8.1	0.076		
	Electrical assembling, installing, and repairing	19	2.7	1.2–6.1	0.019		
Nasca et al. 1988	Narrow definition of EMF exposure	15	1.7	0.80–3.6			Primary CNS tumors
NY State, U.S.A.							
Case-control							
Johnson and Spitz 1989	All electrical occupations	28	1.4	0.88–2.4			Intercranial and spinal tumors
Texas, U.S.A.	Potential electromagnetic field exposure[a]		1.6		<0.07		
Case-control	Electricians[a]	7	3.5		<0.05		
Bunin et al. 1990	Narrow definition: preconception	9	1.3	0.4–4.1			Neuroblastoma
Philadelphia, U.S.A.	Narrow definition: during pregnancy	3	0.3	0.1–1.3			
Case-control							
	Broad definition: preconception	14	1.0	0.4–2.3			
	Broad definition: during pregnancy	7	0.6	0.2–1.6			
Wilkins and Hundley 1990	Electrical occupation						
Columbus, Ohio, U.S.A.	Deapen and Henderson 1986	4	1.6	0.3–9.1			Neuroblastoma
Case-control	Lin et al. 1985: definite (A)	1	nd				
	Lin et al. 1985: possible (B)	5	1.2	0.2–6.4			
	Lin et al. 1985: probable (C)	13	0.5	0.2–1.2			
	Similar to "narrow" in Spitz and Johnson 1985	6	1.9	0.4–9.7			
	Similar to "broad" in Spitz and Johnson 1985	19	0.7	0.3–1.5			

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Table 21. (*concluded*).

Reference / Country	Description	Nervous system tumors: Cases	RR	95% CI	p	NST	Type
Wilkins and Wellage 1996	Presumed EMF exposure: preconception	11	1.3	0.58–3.0			CNS tumors
Columbus, Ohio, U.S.A.	Presumed EMF exposure: pregnancy	9	1.0	0.45–2.4			
Case-control	Welding: preconception	6	3.8	0.95–16			
	Welding: pregnancy	5	2.5	0.67–9.3			
Tornqvist 1998	All cancers						
Sweden	Retrospective: electronic jobs in year before birth	6	0.75	0.24–2.3			CNS tumors
Cohort	Retrospective: electronic jobs at any time	12	2.1 SIR		0.02		
	CNS tumors (estimates)						
	Retrospective: electronic jobs in year before birth	3	0.75	0.14–4.1			
	Retrospective: electronic jobs at any time	6	5.4 SIR		0.002		

Note: RR = relative risk; CI = confidence interval; p = probability; SIR = standardized incidence ratio; OR > 1, 95% CI ≥ 1; OR >1, 95% CI < 1; OR ≤ 1, 95% CI ≤ 1.
[a]Data not included in NIEHS Table 4.17.

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Maternal video display terminal use

Clusters of abnormal pregnancies associated with maternal use of video display terminals (VDT) during pregnancy have been reported in Canada, the United States, Britain, and Denmark (DeMatteo 1986, see Table 24). Although the percentage of abnormal pregnancies among VDT users in Table 24 is high, sample size tends to be low for any one company, which weakens the statistical analysis. The evidence becomes more convincing when the data are combined. A study of 803 pregnancies among data processors in the British Department of Employment indicated that abnormal pregnancies were 36% among VDT users but only 16% among non-users (DeMatteo 1986).

Goldhaber et al. (1988) conducted a case-control study of 1583 pregnant women who attended one of three gynecology clinics in Northern California during 1981 and 1982. They found a significantly elevated risk of miscarriages for the working women who reported using VDTs for more than 20 h each week during the first trimester of pregnancy compared to other working women who reported not using VDTs (OR 1.8, 95% CI: 1.2–2.8). Clerical staff seemed to have higher odds ratios than managers, technical, sales, and blue collar workers. The elevated risk could not be explained by age, education, smoking, or alcohol consumption. No significantly elevated risk for birth defects was found for moderate and high VDT exposure (OR 1.4, 95% CI: 0.7–2.7).

Residential exposure

Two studies by Wertheimer and Leeper, one examining the use of electric blankets and heated waterbeds (1986) and the other examining ceiling cable electric heat (1989), showed that fetal loss increased when conception occurred during the months of increasing cold (October to January) for parents exposed to an EMF source during the night. Homes in which electric blankets and ceiling cables were not used did not show a seasonal pattern of fetal loss. Electric blankets can generate magnetic fields as high as 4 μT at a distance of 5 cm (Table 9) and ceiling cable heating produces ambient magnetic fields of approximately 10 μT and electric fields of 10–50 V/m. Ambient fields in most homes, even those with baseboard heaters, tend to be less than 0.1 μT and 10 V/m (Wertheimer and Leeper 1989).

Timing of exposure may be of particular significance. Liburdy et al. (1993) reported that women sleeping under electric blankets had disrupted melatonin production. The threshold for this effect was between 0.2 and 2 μT, well within the range of the Wertheimer and Leeper (1986, 1989) studies. Among the many functions of melatonin, the regulation of sex hormones are critical for full-term pregnancies.

Paternal exposure

Paternal occupational exposure to electromagnetic fields has also been linked to reduced fertility, lower male to female sex ratio in offspring, congenital malformations, and teratogenic effects expressed in the form of childhood cancer (Nordstrom et al. 1983; Spitz and Johnson 1985; Wilkins and Koutras 1988; Tornqvist 1998).

Nordstrom and colleagues (1983) did a retrospective study of pregnancy outcomes for 542 Swedish power plant employees working in high voltage (130 to 400 kV) substations. In Sweden, 400-kV transmission lines were introduced in 1952 and the pregnancies studied were from 1953 to 1979. A total of 880 pregnancies were classified as (1) spontaneous abortions, (2) perinatal deaths (i.e., stillbirths and deaths before 7 days of age), (3) congenital malformations surviving beyond the perinatal period, and (4) normal outcomes with no malformations and survival beyond the perinatal period. Employees who worked on lines no higher than 380/220 V served as the reference group. There was no significant difference in spontaneous abortions or perinatal deaths among the high voltage switchyard workers but there was an increase of congenital malformations for this group, especially for those with wives aged 30 plus, compared with the reference group (OR approximately 2.5). Two additional differences are worth noting. One is that the male to female sex ratio of offspring was slightly lower (0.92) for high-voltage switch yard workers compared with the reference group (1.16). The second is that couples

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Table 22. Epidemiological studies of leukemia, nervous system tumors, and lymphomas with pre- and post-natal appliance use by parents (from NIEHS, Table 4.24, pp. 203–204).

		Leukemia				Nervous system tumors				Lymphoma									
		Prenatal		Postnatal		Prenatal		Postnatal		Prenatal		Postnatal		Leukemia		NST		Lymphoma	
Reference	Appliance	OR[a]	95% CI[b]	OR[a]	95% CI[b]	OR[a]	95% CI[b]	OR[a]	95% CI[b]	OR[a]	95% CI[b]	OR[a]	95% CI[b]	Pre	Post	Pre	Post	Pre	Post
Savitz et al. 1990	Electric blanket	1.3	0.7–2.6	1.5	0.5–5.1	1.8	0.9–4.0	1.2	0.3–5.7	1.1	0.4–3.6	1.0	0.2–8.6						
	Electric water bed	0.3	0.1–1.2	0.7	0.2–2.5	0.5	0.2–2.0	0.3	0.1–2.7										
	Bedside electric clock	0.9	0.5–1.6	1.4	0.7–2.9	0.8	0.4–1.7	1.1	0.5–2.8	0.5	0.2–1.2	1.5	0.6–4.5						
	Heating pad	0.9	0.4–2.2			0.9	0.4–2.7			2	0.7–5.9								
	Hair dryer			0.5	0.2–1.3			0.6	0.3–1.7			0.7	0.2–2.5						
Hatch et al. 1998	Electric blanket	1.59	1.11–2.29	2.75	1.52–4.98														
	Electric water bed	0.90	0.67–1.21	1.19	0.87–1.62														
	Hair dryer	1.14	0.8–1.61	1.55	1.18–2.05														
	Curling iron	1.06	0.83–1.36	1.74	0.91–3.31														
	Electric clock (digital)	0.98	0.73–1.31	1.20	0.83–1.76														
	Electric clock (dial)	0.81	0.52–1.28	1.69	0.61–4.65														
	TV video game			1.91	1.36–2.68														
London et al. 1991	Bedroom, air conditioner	0.91	0.51–1.66	0.54	0.21–1.25														
	Electric blanket	1.21	0.66–2.29	7.0	0.86–122														
	Electric fan	1.16	0.77–1.75	1.2	0.81–1.8														
	Electric space heatr	1.18	0.62–2.32	1.45	0.82–2.66														
	Electric water bed	0.7	0.34–1.28	1.0	0.45–2.29														
	B&W television			1.49	1.01–2.23														
	Electric clock (all)			1.33	0.90–1.97														
	Electric clock (dial)			1.86	0.71–3.83														
	Electric clock (digital)			1.1	0.71–1.72														
	Color television			1.06	0.66–1.74														
	Curling iron			6.0	0.72–105														
	Electric clippers			1.0	0.06–20														
	Electric hair dryer			2.82	1.42–6.32														
	Microwave oven			0.81	0.48–1.36														
	Video game			1.57	0.80–3.27														

Table 22. (*concluded*).

		Leukemia				Nervous system tumors				Lymphoma									
		Prenatal		Postnatal		Prenatal		Postnatal		Prenatal		Postnatal		Leukemia		NST		Lymphoma	
Reference	Appliance	OR[a]	95% CI[b]	OR[a]	95% CI[b]	OR[a]	95% CI[b]	OR[a]	95% CI[b]	OR[a]	95% CI[b]	OR[a]	95% CI[b]	Pre	Post	Pre	Post	Pre	Post
Preston-Martin et al. 1996*a*	Electric blanket					1.2	0.6–2.2	1.2	0.5–3.0										
	Electric water bed					2.1	1.0–4.2	2.0	0.6–6.8										
	Electric clock (all)					1.0	0.8–1.3	0.7	0.4–1.0										
	Electric clock (dial)					1.1	0.7–1.8	0.6	0.3–1.4										
	Electric heat					1.6	0.8–3.0	1.3	0.7–2.4										
	Electric heat-radiant					1.3	0.2–8.3	1.4	0.4–5.0										
	Microwave					1.4	0.9–2.3	1.0	0.6–1.5										
	Ham radio							2.1	0.2–23.7										
	Hair dryer							1.2	0.7–2.1										
	Curling iron							1.0	0.4–2.5										
	B&W television							0.7	0.4–1.4										
	Baby monitor							0.6	0.2–0.7										
Preston-Martin et al. 1996*b*	Electric blanket					0.9	0.6–1.2	1.0	0.6–1.7										
	Electric water bed					0.9	0.6–1.3	1.2	0.7–2.0										

Note: OR >1, 95% CI ≥1; OR >1, 95% CI <1; OR ≤1, 95% CI ≤1.
[a]OR: Odds ratio.
[b]CI: Confidence interval.

Table 23. Assays of co-initiation and of promotion of mammary cancer in rats (from NIEHS 1998, Table 4.2, page 104 and text pp 89-95). Data are sorted according to magnetic flux density (µT) used in the experiment.

Reference	#/grp	Initiator	Duration: exp't (weeks)	Duration: exp'r (h/d)	Comments on exposure and test organism	Magnetic Flux Density: µT	daily mT/d	total mT	Ranking: Incidence (harm. 2 1 / benef. 1 2)	# tumors (harm. 2 1 / benef. 1 2)	Tumor size (harm. 2 1 / benef. 1 2)	Latency (harm. 2 1 / benef. 1 2)	All: harmful (6 5 4 3 2 1)	All: no (0) / benef. (1 2)	Sum ranks
NTP 1998	100	DMBA, low dose	13	18.5		500	9.25	842			0	0		2	2
NTP 1998	100	DMBA, low dose	26	18.5		500	9.25	1684			0			1	1
NTP 1998	100	DMBA, high dose	13	18.5		500	9.25	842						0	1
Ekstrom et al. 1988	60	DMBA, pre-exposure	25	19–21	Intermittent (5 s on:off)	500	5	875			0	0		2	1
Ekstrom et al. 1988	60	DMBA, pre-exposure	25	19–21	Intermittent (5 s on:off)	250	2.5	438			0	0		2	1
NTP 1998	100	DMBA, low dose	26	18.5		100	1.85	337			0			1	1
NTP 1998	100	DMBA, low dose	26	18.5	60 Hz	100	1.85	337			0			1	2
NTP 1998	100	DMBA, low dose	13	18.5	50 and 60 Hz	100	1.85	168			0	0		2	0
NTP 1998	100	DMBA, high dose	13	18.5		100	1.85	168						0	–1
NTP 1998	100	DMBA, high dose	13	18.5	60 Hz	100	1.85	168						0	–1
Mevissen et al. 1998*a*	99	DMBA	13	24	Homogeneous, no transients	100	2.4	218		0	0			2	–2
Loscher et al. 1993	99	DMBA	13	24	Homogeneous, no transients	100	2.4	218						0	–3
Baum et al. 1995	99	DMBA	13	24		100	2.4	218						0	–3
Mevissen et al. 1996*b*	99	DMBA	13	24	Homogeneous, no transients	50	1.2	109		0	0			2	–2
Beniashvili et al. 1991	25	no initiator	~2 yr	0.5	Strain not provided	20	0.01	7	0					1	–1
Beniashvili et al. 1991	50	MNU	lifelong	0.5	Strain not provided	20	0.01	7	0	0	0	0		4	0
Beniashvili et al. 1991	25	no initiator	~2 yr	3	Strain not provided	20	0.06	44							–4
Beniashvili et al. 1991	50	MNU	lifelong	3	Strain not provided	20	0.06	44			0			0	–6
Anisimov et al. 1996	40	MNU	5 mth	3	Outbred white rats	20	0.06	9							–3
Mevissen et al. 1996*a*	99	DMBA	13	24		10	0.24	22							1
															–1
Loscher et al. 1994	99	DMBA	13	24	Gradient, no transients	0.3–1.0	0.0144	1.3	0	0	0		melatonin decr	3	–2
Mevissen et al. 1998*a*	99	DMBA	13	24	Homogeneous, no transients	0.1	0.0024	0.2			0			1	–2

Note: Studies used female Sprague-Dawley rats and 50 Hz frequencies unless otherwise noted.
exp't = experiment; exp'r = daily exposure.
DMBA = 7, 12-dimethylbenz [*a*] anthracene.
MNU = *N*-methyl-*N*-nitrosourea.
Ranking: 2 = if statistically significant, $p \leq 0.05$; 1 = if "trend" but not statistically significant; # = number of times "no effect" reported.
Sum of ranking: ▬, harmful; ▨, beneficial.

Table 24. Abnormal pregnancies associated with maternal use of video display terminals (VDT) during pregnancy. Data from DeMatteo 1986 (pp. 26–29 in preface).

			Pregnancies		% abnormal pregnancies		
Company, department	Location	Period	Total	Abnormal	All employees	VDT users	VDT make/model
Federal Government, Solicitor-General's Office	Ottawa, Ont.	1979–1982	8	7	88	100	Micom 2000
Defense Logistics Agency	Atlanta, Ga.	1979–1980	15	10	67	100	IV Phase Motorola
Toronto Star, Classified Ad Department	Toronto, Ont.	1979–1980	7	4	57	100	Not specified
Dorval Airport, Air Canada ticket agents	Montreal, Que.	1979–1981	13	7	54	100	Raytheon and Westinghouse
Queen's University, Douglas Library	Kingston, Ont.	1980–1984	6	6	nd	100	GEAC VDT
Surrey Memorial Hospital, Accounts Department	Surrey, B.C.	1978–1982	7	6	nd	86	Perkin-Elmer 1200 VDTs
City's Public Library	Aarhus, Denmark	nd	10	8	nd	80	Not specified
Fire Services, Computer Control Centre	Greater Manchester, England	1984–1986	10	8	nd	80	Not specified
Bank	Grimsby, England	1977–1978	5	4	nd	80	Not specified
British Telecom, Data Processing Centre	Bristol, England	1983–1984	5	4	nd	80	Not specified
Sears Roebuck, Computer Centre	Dallas Tex.	1979–1980	12	8	nd	67	IV Phase Motorola
Pacific Northwestern Bell	Renton, Wash.	1980–1981	5	3	nd	60	Motorola display products
Toronto's Old City Hall, Courthouse	Toronto, Ont.	1977–1981	19	11	nd	58	Not specified
General Telephone of Michigan, VDT operators	Alma, Mich.	1981–1983	32	17	nd	53	Tandy TRS-4 VDT
United Air Lines, telephone sales reservation clerks	San Francisco, Calif.	1979–1984	48	24	nd	50	Incoterm 10306 VDT
Southern Bell, telephone operators on fifth floor	Atlanta, Ga.	1979–1980	15	6	nd	40%	Computer Console Inc., 4500
Department of Employment, data processors	Britain	nd	803	nd	16[a]	36%	Not specified
Japanese General Council of Trade Unions	Japan	nd	250	~80	nd	33%	Not specified

Note: nd: no data
[a]For non-VDT users

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experienced some difficulty conceiving when the husband worked in a high-voltage switch yard (200 or 400 kV) (OR approximately 2.5). In vivo studies with rats showed that exposure to high electric fields reduced plasma testosterone concentrations and reduced sperm viability (Andrienko 1977; Free et al. 1981).

In a follow-up study, Nordenson et al. (1984) screened 20 switchyard workers exposed to 400 kV lines for chromosomal anomalies in peripheral lymphocytes and compared the results with 17 controls consisting of salesmen and clerks. They found a significant increase in the number of chromosomal aberrations among the switchyard workers. The aberrations consisted of gaps, chromatin breaks, acentric fragments, dicentrics, and tricentrics as well as polyploidy, endoploidy, and premature chromosome condensation. Smoking was also associated with a slight increase in abnormal chromosomes and was corrected for in the study. The number of abnormal chromosomes per 100 cells was 2.6 for non-exposed non-smokers; 3.8 for non-exposed smokers; 5.4 for exposed non-smokers; and 6.3 for exposed smokers. The results indicate almost a 2-fold increase in chromosomal aberrations among switchyard workers.

Shandala et al. 1986 studied the effects of 50-Hz fields of 1–5 kV/m on rat reproduction and found an increase in the duration of the estrous cycle and gestation, decreased spermatogenesis and sperm concentrations, more atypical sperms, histopathological changes in the testes, and more fetal and post-fetal mortality. The effect occurred only when the females were exposed to the electromagnetic field.

Wilkins and Koutras (1988) conducted a case-control study of Ohio-born children who had died of brain cancer during 1959 and 1978. Significantly higher odds ratios for offspring with brain tumors were observed for fathers employed in five industry groupings: (1) agriculture, forestry, fishing: OR = 2.4; (2) construction: OR = 2.3; (3) metal: OR = 1.8; (4) machinery: OR = 1.7; and (5) transportation: OR = 1.6. A more refined analysis showed that case-fathers were more likely than control-fathers to be (1) electrical assemblers, installers, and repairers (OR = 2.7, 95% CI = 1.2–6.1); (2) welders and cutters (OR = 2.7, 95% CI = 0.9–8.1); or (3) farmers (OR = 2.0, 95% CI = 1.0–4.1). Although chemicals cannot and should not be ruled out as potential confounders, the industries mentioned above (except for farming) tend to have higher than average EMF exposure (Table 12).

Johnson and Spitz (1989) conducted a population-based case-control study of 499 children who died in Texas from intracranial and spinal cord tumors during the period 1964–1980. They report a statistically significant increased risk of childhood neuroblastoma (tumor starts in nerve cells) relative to paternal employment at the time of birth in occupations that potentially involve exposure to low frequency fields as well as an array of chemicals. Odds ratio for occupational EMF exposure was 1.6 ($P < 0.07$) and for electricians it was 3.5 ($P < 0.05$). Four of the seven children of electricians were diagnosed with tumors in the brainstem. Brainstem gliomas (tumor starts in glial or supportive cells) generally account for 9–13% of pediatric patients with central nervous system tumors whereas in this study they accounted for 14% for all cases and 15% for cases whose fathers were employed in electrical occupations.

In both this and the previous study, the role of occupational chemical exposure, particularly organic solvents and metal aerosols, is likely to be important. A paternal occupational study that can differentiate between EMF and chemical exposure and the risk of childhood cancers is needed.

The data presented in these studies suggest that miscarriages and possibly birth defects are linked to maternal EMF exposure, while childhood nervous system tumors are associated with paternal EMF and chemical exposure.

6.3. Depression

Depression is an affective disorder that seems to be more prevalent among people born in the latter part of the 20th century than among previous generations (Berkow et al. 1997). Symptoms vary. Vegetative depression is characterized by feelings of prolonged sadness, loss of appetite often resulting in weight loss, disturbed sleep, withdrawal from social activities, reduced libido. Agitated depression shares some of these symptoms but is also associated with excessive restlessness and agitation.

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As many as 25 to 30% of the population are likely to experience some form of excessive mood disorder during their lifetime but only 10% are likely to require medical attention.

Depression may be triggered by a traumatic event in one's life (situational depression) or by a biochemical imbalance (endogenous depression). Low levels of several neurotransmitters and neurohormones (serotonin, melatonin, and catecholamine) have been strongly associated with depression (Berkow et al. 1997).

Several lines of evidence suggest that depression is associated with and may be induced by exposure to electromagnetic fields. Epidemiological studies have found higher ratios of depression-like symptoms (Poole et al. 1993) and higher rates of suicide (Reichmanis et al. 1979) among people living near transmission lines.

Poole et al. (1993) conducted a telephone survey of people living adjacent to a transmission line and a control population selected randomly from telephone directories. Questions related to depression were based on the Center for Epidemiologic Studies Depression scale. There was a higher percentage of depressive symptoms among people living near the line compared with the control population. The odds ratio was 2.1 with a 95% confidence interval between 1.3 and 3.4. Demographic characteristics, environmental attitudes, and reporting bias do not appear to influence the OR. The association between proximity to the transmission line and headaches (migraine and other) was much weaker (OR 1.2 and 1.4, respectively).

Depressive symptoms as well as fatigue, irritability, and headaches have also be reported for occupational exposures (DeMatteo 1986; Wilson 1988).

Another line of evidence comes from in vivo studies that report desynchronization in pineal melatonin synthesis in rats exposed to electromagnetic fields (Wilson 1988). The association between depression and disrupted melatonin secretion is well documented (see Reiter and Robinson 1995; Breck-Friis et al. 1985; Cavallo et al. 1987; Wetterberg et al. 1992; Lewy et al. 1982). Exposure to artificial light (a different part of the electromagnetic spectrum) in the evening also disturbs night-time melatonin synthesis (Lewy et al. 1987), which suggests that timing of EMF exposure may be critical.

6.4. Alzheimer's disease

In contrast to cancers, very few studies have examined the association between occupational EMF exposure and Alzheimer's disease. One case-control study by Sobel et al. (1995) included three independent clinical series of non-familial Alzheimer's disease in Finland (two series) and California, U.S.A. (one series). Non-familial Alzheimer's was selected to minimize the genetic influences in the etiology of this disease. A total of 387 cases and 475 control were included in the combined series and were classified into two EMF categories (medium/high and low exposure in primary occupations). Significantly elevated odds ratios (OR 3.9; 95% CI 1.7–8.9) were observed for the combined data sets for females working primarily as seamstresses and dressmakers. The OR for males was also above 1 (OR 1.9) but was not statistically significant.

Sewing machines generate very high magnetic fields (see Fig. 4, Table 13), much higher than most electrical occupations. More studies focused on Alzheimer's disease and EMF exposure with a much broader occupation base are needed before any definitive statements can be made. The highly significant OR in this study is disturbing if the results can be generalized to a much broader population.

6.5. The elusive mechanism

The effect of an environmental pollutant, such as DDT, lead, or asbestos, is often observed long before the mechanism of action is understood. This delay does not negate the original observation. With respect to electric and magnetic fields, several promising mechanisms related to the biological responses are currently being considered. For low frequency, low intensity fields these include but are not limited to (1) melatonin production, (2) mitosis and DNA synthesis, and (3) ion fluxes particularly that of calcium.

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Melatonin production

Melatonin is a neurohormone that regulates sleep cycles, sex hormones, and reproduction. It is produced by the pineal gland, a small pea-shaped gland connected to the optic nerve and located in the middle of the brain near the hypocampus . The pineal gland is light sensitive and in lower life forms is just below the skin surface. The chameleon's ability to change its body pigmentation to mimic that of its surroundings is attributed to the pineal gland. In eastern cultures the pineal gland has been associated with the third eye.

Melatonin follows several natural cycles. It is higher at night than during the day and is associated with restful sleep. It is higher in young people, particularly infants who spend a lot of time sleeping, as opposed to the elderly who have difficulty sleeping. It is higher in winter than in summer and it has been linked with changes in serotonin levels and seasonal affective disorder (SAD), a form of depression that is accompanied by prolonged periods of fatigue. Melatonin has been used to treat sleep disturbances associated with jet lag.

The evidence linking changes in the melatonin cycle to EMF exposure is growing. We now know that the pineal gland can sense changes in electromagnetic frequencies other than those associated with visible light including static and power frequencies fields (Liburdy et al. 1993) as well as solar flares (Hansen et al. 1987). Timing of exposure is critical for melatonin production. If EMF exposure occurs in the evening it can interfere with night-time concentrations of melatonin and affect sleep but if it occurs earlier in the day it has no effect on melatonin production (Reiter and Robinson 1995).

Melatonin also controls the concentrations of sex hormones. High levels of melatonin are associated with lower levels of estrogen. Some types of breast cancer are estrogen-sensitive which means their growth is promoted by estrogen. High levels of melatonin (which suppresses estrogen levels) may have a protective effect on this form of cancer. Conversely, if normal night-time peaks of melatonin are reduced and estrogen levels remain high, this form of breast cancer is likely to be more aggressive.

Studies of women sleeping under electric blankets had lower night-time melatonin levels (Wilson et al. 1990). This study shows that melatonin regulation in influenced by power line frequency at intensities commonly found in the home.

Since melatonin controls reproductive cycles it may also explain some of the miscarriages experienced by women who either sleep in a high EMF environment (electric blankets, waterbeds, or ceiling-cable heating systems) or work with video display terminals that generate power frequency and higher frequency fields (Wertheimer and Leeper 1986, 1989; Goldhaber et al. 1988).

Melatonin has also been heralded as an natural anti-cancer chemical (Reiter and Robinson 1995). Its antioxidant properties may help control the growth of other forms of cancer. Various forms of cancer have been linked with EMF exposure. If endogenous melatonin concentrations are reduced, the natural ability of the body to fight cancerous cells may be compromised, resulting in a more aggressive spread of the cancer.

Melatonin is synthesized from serotonin, a neurotransmitter associated with depression (Reiter and Robinson 1995). Imbalances in the serotonin/melatonin cycle may account for depressive symptoms experienced by people living near power lines or working in high electromagnetic environments.

Melatonin is linked with some of the key responses to electromagnetic fields, namely breast cancer as well as other forms of cancer, miscarriages, and depression, and for this reason is one of the more likely candidates for explaining the mechanism responsible for some of the bioeffects of electromagnetic fields.

Mitosis and DNA synthesis and chromosomal aberrations

The area of cell proliferation is complex but changes in mitosis associated with fluctuations with the earth's magnetic field and with various ac frequencies has been reported. Liboff et al. (1984) examined the effect of electromagnetic fields on DNA synthesis in human fibroblasts. They exposed the cells to frequencies between 15 Hz and 4 kHz and intensities from 2.3×10^{-6} to 5.6×10^{-4} T (2.3 to

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560 μT) and measured the incorporation of tritiated thymidine. DNA synthesis was enhanced during the 24-h incubation. The threshold for this effect is estimated to be between 5 and 25 μT/s (product of magnetic flux density (rms) and frequency) and is within the range associated with abnormal chick embryo development (10 μT/s). Reduced latency period and enhanced tumor size of mammary cancer in rats exposed to EMF suggest a more rapid growth rate (Beniashvili et al. 1991; Baum et al. 1995; Loscher et al. 1993).

Ion fluxes and molecular resonance

If resonance occurs in atoms or molecules (as has been suggested for some physiologically important monovalent and divalent ions, including lithium, potassium, sodium, and calcium) then these frequencies may very well have biological consequences (Blackman et al. 1994). The model that has been proposed and has received empirical support (but has also been criticized) is that of cyclotron resonance. The frequencies at which ions resonate depends on their mass, charge, and the strength of the static (geofield) magnetic field (Fig. 5). Alternating current at the resonant frequency can transfer more energy to these ions and thus disturb their internal movement. The effects are location specific which may explain the discrepancy in some epidemiological- and laboratory-based studies.

Calcium has received the most attention in this regard. Brain tissue of newly hatched chicks released calcium ions when exposed to a radio frequency modulated at specific frequencies (15, 45, 75, 105, and 135 Hz, for example) which suggested that specific frequencies windows are important for biological effects (Adey 1980; Blackman et al. 1985). Calcium is critical for many cell processes and changes in its flux could have significant and diverse effects on biota.

7. Electromagnetic fields in a broader context

7.1. Occupational exposure

Occupational exposure to electromagnetic field has been studied as it affects workers (see section 6.1 on Cancer) as well as their children (section 6.2 Reproduction).

Different types of reproductive problems are associated with maternal, as opposed to paternal, exposure. Mothers exposed to EMF from VDT during pregnancy may have a higher risk of miscarrying (DeMatteo 1986; Goldhaber et al. 1988). Paternal exposure, in contrast, has been associated with reduced fertility, lower male: female sex ratio among offspring; congenital deformities; and the risk of offspring developing central nervous system (CNS) tumors (Nordstrom et al. 1983; Wilkins and Koutras 1988; Johnson and Spitz 1989).

The higher risk of developing cancers, particularly leukemias, brain tumors, and breast cancer, has been covered in section 6.1. A number of the solvents and metal aerosols in the work environment are known to be carcinogenic and since EMFs have been shown to promote cancer, the two may be acting synergistically. This is an area that requires carefully conducted research to determine what aspect of the electromagnetic field and chemicals in the workplace, separately or in combination, are responsible for the tumors, if indeed there is a causal connection. Detailed studies of EMF exposure in the workplace are critical for this type of research and should include exposure to both magnetic and electric fields since occupational exposure to electric fields may be considerable.

7.2. Other than 50 and 60 Hz (static to microwave frequencies)

The focus in both documents is on frequencies associated with alternating current (ac) power distribution systems, namely 60 Hz in North America and 50 Hz elsewhere. Direct current (dc) power distribution is not discussed in any detail nor are frequencies other than 50 and 60 Hz. Yet, in occupational and residential settings people are exposed to frequencies both lower and higher than those generated by our power distribution systems.

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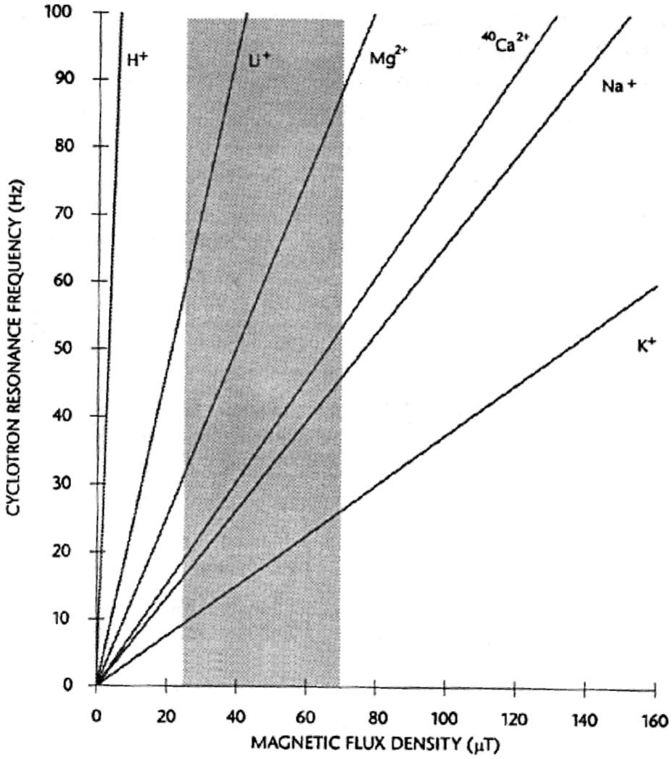
Fig. 5. Cyclotron resonance frequencies of hydrogen (H^+), lithium (Li^+), sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}) ions at different static magnetic fields. The shaded area relates to the geomagnetic field produced by the earth. (Reprinted with permission from M. Milburn and M. Oelbermann, *Electromagnetic fields and your health*. Copyright 1994 by New Star Books, Vancouver, B.C.)



Static magnetic fields, considerably higher than those generated by the earth, are common among DC welders and those exposed to magnetic resonance imaging (MRI).

At the low end of the electromagnetic spectrum, subharmonics of the ac power distribution system and certain forms of communication (on submarines for example) are below 60 Hz.

Above 60 Hz we are exposed to harmonics of the power distribution frequency (for 60 Hz harmonics include 120, 180, 240, 300 Hz, etc.). On airlines the alternating current operates at 400 Hz and on railways it operates at 300 Hz, although frequencies from 5 to 2560 Hz have been measured in electric trains, buses, subways, and trolley cars (US DOT 1993*a*,*b*). Those who receive electrical anesthesia are exposed to 700 Hz frequencies. Computers generate frequencies in the kilohertz and megahertz range (DeMatteo 1986) and cell phones operate within the microwave band of the electromagnetic spectrum between 900 MHz (analog) to 2 GHz (digital). Frequencies generated by various occupations is shown in Table 14.

Microwave frequencies

The proliferation of frequencies in the microwave band is particularly disturbing, since these frequencies have been associated with cataract formation, various forms of cancer, reproductive problems (miscarriage, altered sex ratios, birth defects), and changes in brain wave activity (Frey 1967; Goldsmith 1995; Marino 1988; Ouellet-Hellstrom and Stewart 1993; Szmigielski 1996). Microwave exposure from wireless communication systems is as much a public concern as is 60 Hz exposure from power lines

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and it is likely to become of even greater concern with the continued growth of the wireless telecommunication industry. Neither the NRC nor the NIEHS committees examined this form of exposure.

Radio and television broadcasting as well as radar have been with us for decades and an excellent review is provided by Steneck (1984). Satellite communication is a relatively recent phenomenon but one that has been rapidly proliferating to provide more and better signals to television viewers around the world. Satellites have both uplink and downlink stations and are blanketing the planet with technologically generated radio frequencies.

Cellular technology and wireless telecommunication have progressed rapidly during the past 20 years, and these technologies also operate at the microwave region of the electromagnetic spectrum. Millions of cell phone users world wide are exposed to the microwave radiation whenever they place a cell phone near their head. The ever present cell phone towers with their multiple antennas are exposing users and non-users alike to microwave frequency radiation.

Since buildings and trees can block some of the microwave radiation, more cell phone towers are being erected, particularly in large densely populated cities with numerous tall buildings. As of December 1999 there were more than 5000 wireless telecommunications antennae sites, some with multiple antennas, in the City of Toronto (Bedford and Ridge 1999) and the telecommunication industry is constantly requesting more sites for their customers. Towers are found in commercial, industrial, and residential areas and have even been erected on schools and hidden in church towers. Local planning authorities are the ones who need to deal with the requests and will often grant a license based on federal guidelines for radio frequency radiation (Safety Code 6, Health Canada). Publicity and public concern are forcing municipal planning authorities to reassess where cell phone towers can be sited. The City of Toronto Public Health Authority is currently reviewing Canada's federal standards and is considering setting a guideline that would be one one hundredth the standard set by Health Canada (Safety Code 6).

The Safety Code 6 (SC6) standard (Table 25) is based on thermal effects and as such may not protect the public against the non-thermal effects of radio frequency radiation (RFR). In July 1998, The Radiation Protection Bureau of Health Canada asked the Royal Society of Canada to review the adequacy of SC6 for protecting public health. The Royal Society's report, entitled *A Review of the Potential Health Risks of Radiofrequency Fields from Wireless Telecommunication Devices* became available in the summer of 1999.

The microwave band of the electromagnetic spectrum extends from 300 MHz to 300 GHz and is the upper part of the radio frequency region (Fig. 2). In this part of the electromagnetic spectrum the intensity of the energy is expressed as power density (W), which is the power incident on a surface divided by the area of that surface (see eq. [1]).

$$[1] \qquad W = E \times H$$

where W = power density (W/m^2), E = electrical potential (V/m) , and H = magnetic field strength (A/m).

Note that magnetic field strength (H) can be converted to the magnetic flux density (B) by eq. [2] or [3].

$$[2] \qquad B = uH(A/m) \qquad \text{SI units for } B \text{ measured in tesla (T)}$$

$$[3] \qquad B = H(A/m) \qquad \text{cgs unit for } B \text{ measured in gauss (G)}$$

where B = magnetic flux density, H = magnetic field strength, and $u = 1.26 \times 10^{-6}$ henry/m in a vacuum, air, and tissues, A = amps, m = metres

Note also that specific absorption rate (SAR) represents the rate of deposition into tissue. It is also used for standards and is expressed in units of watts per kilogram.

The expert panel convened by the Royal Society came up with the following conclusions regarding Safety Code 6.

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Table 25. Exposure limits for radio frequency radiation applicable to base station transmitters and cellular phones according to Safety Code 6, Health Canada (Royal Society of Canada 1999).

		Power density limit, W/m^2	
Base station transmitters	Frequency (f) MHz	Workers	Public
	300–1 500	f/30	f/150
	1 500–15 000	50	10
		Specific absorption rate (SAR), W/kg	
Cellular phones	Exposure conditions	Workers	Public
	Whole body (averaged over the whole body mass)	0.4	0.08
	Head, neck and trunk (averaged over any 1 g of tissue)	8.0	1.60
	Limbs (averaged over any 10 g of tissue)	20.0	4.00

(1) The panel concluded that for whole body exposure the limits (0.4 W/kg for worker and 0.08 W/kg for public) are adequate but that the much higher limits for partial body exposure (8 W/kg for head, neck, trunk and 20 W/kg for extremities) may not be sufficient to protect against harmful effects and that time-limits should be set. The US Food and Drug Administration limits exposure of the head to 8 W/kg and of the extremities to 12 W/kg for a maximum of 5 min.

(2) The panel identified the eye as a particularly sensitive organ, because of its inability to dissipate heat, and for that reason questions the SC 6 for exposure to the head of 8 W/kg for workers and suggests that an interim limits should be set at 1.6 W/kg, the same as for the general public. They also recommended research in this area.

(3) The panel distinguished between biological effects and health effects and agreed that, while biological effects have been demonstrated in laboratory studies, convincing health effects have not been demonstrated. They recommended more epidemiological and clinical research with proper assessment of exposure and more genotoxicological research.

(4) The panel distinguished between thermal and non-thermal effects and concluded that "exposure to RF fields at intensities far less than levels required to produce measurable heating can cause effects in cells and tissues." These biological effects at low, non-thermal exposure levels below Safety Code 6 include "alteration in the activity of the enzyme ornithine decarboxylase (ODC), in calcium regulation, and in the permeability of the blood–brain barrier ... Some of these biological effects brought about by non-thermal exposure levels of RF could potentially be associated with adverse health effects."

(5) Of the **biological effects** the panel considered cell proliferation, calcium efflux, cell membrane effects, blood–brain barrier, Ornithine Decarboxylase (ODC) activity, melatonin, behaviour and biophysical mechanisms. Many of these are the same end points documented for extremely low frequency electromagnetic fields.

(*a*) **Cell Proliferation:** The panel concluded that "at low intensity non-thermal levels RF fields do not appear to alter cellular proliferation rates" although they do mention evidence of increased cell proliferation of LN71 glioma cells and Chinese hamster ovary cells and evidence that cell proliferation can also be reduced depending on exposure time.

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(*b*) **Calcium Efflux**: Calcium efflux is affected only when RF fields are modulated with extremely low frequencies, in other words when they act as carriers for other frequencies. This happens at intensities below the Safety Code 6 limit. The panel concluded that “it is not clear that RF field exposures from wireless communications devices would affect calcium regulation in the brain, or that effects of this type would have any health consequences.

(*c*) **Cell Membrane Effects:** RF fields appear to affect membrane channels as demonstrated by altered fluxes of sodium, potassium, and calcium ions, although the specific biophysical mechanism is not known.

(*d*) **Blood–brain Barrier (BBB)**: Radio frequency radiation, below the Safety Code 6 limit has been shown to increase the permeability of the blood–brain barrier in some but not all studies. The inconsistencies among results suggests that either the low-level RF exposure is not significant or that the permeability is altered at a specific carrier or modulation frequency.

(*e*) **Ornithine Decarboxylase (ODC) Activity**: The activity of the enzyme, Ornithine Decarboxylase, increases at levels below SC 6 when the field is modulated with extremely low frequencies and when digital cell phone fields are pulsed with a low frequency component. The panel noted that while there is an association between cancer and ODC activity, not all stimuli capable of increasing ODC activity promote cancer.

(*f*) **Melatonin**: The panel concluded that, while the effects of extremely low frequency electromagnetic fields and the effects of light on melatonin synthesis have been studied, very little research has been conducted on the effects of RF on melatonin and the few studies that have been reported are inconclusive.

(*g*) **Behaviour**: Radio frequency fields may affect the endogenous opioid system in rats and thus impair their ability to perform tasks requiring spatial memory. This was not linked with any adverse health effects.

(*h*) **Mechanistic Considerations:** The panel concluded that non-thermal effects of RF field exposure have been observed, but the biophysical mechanism responsible for those effects is poorly understood.

(6) The panel’s assessment of the **health effects** are based on toxicological studies of DNA damage, tumor growth, and longevity of laboratory animals; on epidemiological studies; and on clinical studies of brain function.

(*a*) Based on **toxicological studies** the panel concluded that there is little evidence that exposure to RF fields at non-thermal levels either induces tumors or promotes tumor growth in animals. The panel states “although a few studies have shown a significant increase in tumor promotion in the exposed groups, the significance of these findings is unclear pending replication of the results by other investigators.” They also conclude that “more research should be done in this are to clarify the ability of RF fields to cause DNA damage.”

(*b*) The panel concluded that the **epidemiological studies** based on radio frequency fields are of limited value because of poor exposure assessment. “Overall, these studies do not provide conclusive evidence of adverse health effects from RF exposure. However, given the limitations of the currently published studies in this area, particularly the difficulty in determining the precise nature of the exposure to RF fields that people have actually received, more research is required on RF field exposure and human health.”

(*c*) The **clinical studies** using RF fields were based on neurological health and brain function in humans. The panel concluded that the studies failed to show any adverse health effects attributable to RF exposure.

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(*d*) Overall, there are no clear adverse health effects related to RF exposure based on the studies available. Better monitoring of exposure is needed if future epidemiological studies are to provide useful information.

(7) The panel concluded that "because of the low field strengths associated with public exposure to RF fields from wireless telecommunications base station transmitters, neither biological nor adverse health effects are likely to occur."

(8) They also concluded that RF fields from "cell phones could be of sufficient intensity to cause the type of biological effects described previously, such biological effects are not known to be associated with adverse health effects."

(9) The panel concluded that the area of differing sensitivity should be examined in greater detail and that sub populations (including children, pregnant women, or the elderly) may be at greater risk to RF fields as they have been to other environmental contaminants. Some people can sense RF fields, but the clinical and epidemiological studies to date are inconclusive.

(10) The information available on non-thermal effects requires clarification before it can be included in Safety Code 6.

The similarities between radio frequency bioeffects and power line frequency bioeffects are considerable and should be examined together as part of the EMF continuum. The panel did not consider some of the recent research dealing with headaches, brain tumors, and cell phone use, since its focus was on wireless telecommunication towers rather than on cell phone use per se.

7.3. Electromagnetic sensitivity

One of the most detailed and carefully controlled experiments conducted to determine the existence of electromagnetic field sensitivity is that by Rea and co-workers (1991). Rea et al. used a four-phased approach that involved establishing a chemically and electromagnetically "clean" environment; screening 100 self-proclaimed EMF-sensitive patients for frequencies between 0 and 5 MHz; retesting positive cases ($n = 25$) and comparing them with controls; and finally retesting the most reactive patients ($n = 16$) with frequencies to which they were most sensitive during the previous challenge.

Sensitive individuals responded to several frequencies between 0.1 Hz and 5 MHz but not to blank challenges. The controls used did not respond to any of the frequencies tested.

Most of the reactions were neurological (such as tingling, sleepiness, headache, dizziness, and in severe cases unconsciousness) although a variety of other symptoms were also observed including pain of various sorts, muscle tightness particularly in the chest, spasm, palpitation, flushing, tachycardia, edema, nausea, belching, pressure in ears, burning and itching of eyes and skin (Fig. 6).

In addition to the clinical symptoms, instrument recordings of pupil dilation, respiration, and heart activity were also included in the study using a double-blind approach. Results indicate a 20% decrease in pulmonary function and a 40% increase in heart rate. Patients sometimes had delayed or prolonged responses. These objective instrumental recordings, in combination with the clinical symptoms, demonstrate that EMF sensitive individuals respond physiologically to certain EMF frequencies.

This is not the only study on EMF-sensitive but it is perhaps one of the best. Others document similar symptoms.

7.4. Biomagnetism and magnetobiology

Studies of magnetic fields and biota can be classified into two broad categories: biomagnetism and magnetobiology. The first refers to the study of endogenous (internally generated) magnetic fields while the second refers to the effects of exogenous (externally generated) magnetic fields on biological systems.

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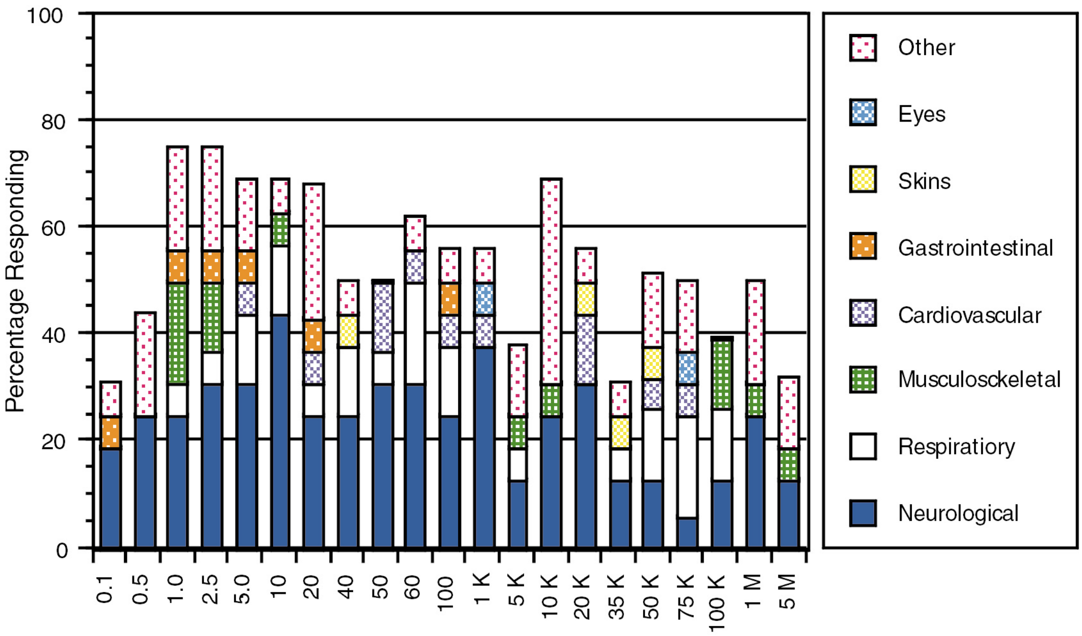
Fig. 6. Responses of 16 electromagnetically sensitive patients to experimental electromagnetic frequencies ranging from 0.1 Hz to 5 MHz in a clean environment. (Data adapted from Rea et al. 1991.)



Biomagnetism research has developed recently and has been greatly facilitated by the invention of extremely sensitive magnetometers. Since all living organisms generate weak magnetic fields about a million-fold weaker than that of the earth's magnetic field, shielded chambers and sensitive measuring devices are necessary to detect these weak fields. The Superconducting Quantum Interference Device (SQuID) appeared in the 1970s and has enabled researchers to measure extremely weak magnetic fields. Most of the research has concentrated on the magnetic fields generated by the heart (magnetocardiography, MCG), brain (magnetoencephalography, MEG), muscles (magnetomyography, MMG), nerves (MNG), eye ball (magnetooculography, MOG), or retina (magnetoretinography, MRC). Characteristics fields are being documented using non-invasive, non-contact technology with the hope that these fields can ultimately be used for diagnostic purposes, like electrocardiograms (ECG) and electroencephalograms (EEG).

Natural magnetite was detected for the first time in bacteria in 1975 (Blakemore 1975). Blakemore discovered magnetotactic bacteria in the sediments of Cape Cod, Massachusetts, that moved in the direction of the geographic north pole. In the northern hemisphere this means a movement into the deeper sediments where concentrations of gaseous oxygen are low, enabling these anoxic species to survive. These bacteria contain a chain of iron nodules that resembles a pearl necklace within the cell. These magnetic inclusions serve as a magnetic dipole that orients the cells in a magnetic field.

Ferromagnetic particles have been found in pigeons, bees, butterflies, mollusks, algae, migratory fishes (tuna, salmon, blue marlin), sea turtles, dolphins, whales, rodents, monkeys, and humans (Walcott et al. 1979; Mather and Baker 1981; Beason and Nichols 1984; Walker et al. 1984; Kirschvink et al. 1985; Ogura et al. 1992; Hsu and Li 1994; Kavaliers and Ossenkopp 1994; Zoeger et al. 1981; Jones et al. 1982; Baker et al. 1983; see review by Kholodov et al. 1990). Location of the ferromagnetic particles varies among species, although for many it is between the dura mater and the skull. It is assumed that these magnetic inclusions are used to sense the earth's magnetic field.

Studies with homing pigeons showed that they rely on the location of the sun, landforms, and a built-in geomagnetic detection system for navigation. Pigeons wearing frosted contact lens and a helmet that

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distorted their ability to sense the earth's magnetic field were unable to find their way home until the artificial magnetic field was deactivated (Keeton 1971).

Just as the pigeons responded to the magnets in their helmet, migrating birds responded to alternating current electromagnetic fields generated by Project Seafarer (Larkin and Sutherland 1977). During operation antennae generated sinusoidal waves between 72 and 80 Hz. Radar was used to track birds flying over these antenna at night at an altitude of 80 to 300 m where electric fields were calculated to be 0.07 V/m and magnetic fields were 0.1 to 0.5 μT. Birds responded differently when the antennae system was operating. Results indicate that birds can detect low-intensity alternating current magnetic fields within a few seconds and that orientation involving the use of magnetic cues may be used during flight. Natural magnetic disturbances (magnetic storms) have been known to interfere with bird migration. A "magnetic front" in June 1997 is blamed for disorienting tens of thousands of racing pigeons that flew the English Channel to France to mark the British Racing Pigeon society's centenary. Similarly high voltage transmission lines may interfere with bird migration, just as undersea power lines and antennas may interfere with the migration of marine organisms.

In humans the highest magnetic fields associated with iron deposits are found in sinus bones, pineal gland, turbinated bone, and dura mater in the brain. Their function has yet to be determined. Hemoglobin in red blood cells also has a high iron content. Karmilov found that patients suffering from cancer show certain modifications of blood magnetic properties (in Kholodov et al. 1990).

Magnetic fields have been detected in two types of tumor in mice: US-8 lymphoma and Lewis lung tumor (Kirschvink et al. in Kholodov et al. 1990). Cultivated tumor cells were exposed to various magnetic fields to evaluate their impact on tumor growth. The Lewis tumor did not react to external magnetic fields but the US-8 cells did respond. Very high magnetic fields (mT) stimulated cell growth at 2000 Hz, and inhibited cell growth at 60 Hz (Gabrah and Batkin in Kholodov et al. 1990). Biomagnetism and magnetobiology are two areas that deserve more study.

8. Comments on bias and consistency

8.1. The question of bias

Prejudicial bias is something that scientists try to avoid since their credibility depends on an open unbiased approach to scientific hypothesis testing. By prejudicial bias I refer to someone with a firmly held opinion whose mind is not open to evidence that might contradict that opinion. Cultural bias, a type of bias associated with different scientific disciplines (and indeed different cultures), refers to the amount of proof needed before an opinion is considered valid. This type of bias, or level of acceptance, is considered the norm within a scientific subculture and is taught to young scientists as part of their training. Since variability among data sets and within scientific subdisciplines differs, the standards for acceptance are culturally defined. Physical scientists are accustomed to precise measurements while biological scientists, particularly those who work in the field, are accustomed to considerable variability in their data sets and have developed techniques to detect low signal-to-noise ratios. For this reason, two scientists with different expertise will often interpret the same data differently. One hears the noise while the other hears the signal. It is seldom easy to differentiate between prejudicial and cultural bias.

As I was reading the NRC Report I became aware of two strong cultural biases that were in conflict. One represented the views of epidemiologists and the other that of physiologists. By this statement I am not implying that all physiologists or that all epidemiologists have similar views on the bioeffects of EMFs but rather that two strong culture perspectives were obvious in the NRC Report. This conflict was also evident in the NIEHS document but was presented in a more balanced way than in the NRC document. The overall conclusions presented in the NRC document were much more strongly influenced by the physical scientists and for this reason I found the NRC document culturally biased.

Whenever a detectable biological response was observed the authors of chapter 3 (Cellular and Molecular Effects) and chapter 4 (Animal and Tissue Effects) would end each paragraph by trying to

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downplay the effect in some way. This happened so frequently that I began to think "Methinks, thou doth protest too much!"

For example: Yes there is a biological response ...

(1) but there is no evidence that it is an **adverse** response.

> A decrease in performance accuracy on this task does not imply a deleterious effect of magnetic-field exposure" (NRC 1997, p. 93).

(2) but there is no evidence for **humans**.

> The positive result reported when power-frequency electric or magnetic fields were combined with certain genotoxic and nongenotoxic carcinogens are an extremely interesting observation, but one that is also extremely difficult to interpret in terms of its implications, if any, for potential carcinogenesis in human populations. (NRC, p. 57)
>
> "Unfortunately, on the basis of seemingly meager data, Marino and Becker (1977) concluded that such field exposures might have implications for human health." (NRC, p. 103).

(3) but the study has not been **replicated**.

> Their provocative findings, however, are near the limit of plausibility and must be replicated before the results can be accepted. (NRC, p. 101).

(4) but the study has not been **replicated by others**

> Most of the studies, even those that appear to be carefully done and reliable, have not been independently replicated and thus cannot be considered conclusive. (NRC, p. 63)

(5) but there were problems with the **statistical methods**.

> ... the statistical methods used in this study did not take into account the multiple hypotheses that were being tested simultaneously; such a consideration would render the differences between sham-exposed and exposed statistically insignificant. (NRC, p. 99).

(6) but the **exposures** were too high.

> The committee's overall conclusion based on analysis of in vitro experimentation is that magnetic-field exposures at 50–60 Hz have been shown to induce changes in cultured cells only at field strengths that exceed residential exposure levels by factors of 1 000 to 100 000. (NRC, p. 53).

(7) but there were shortcomings with **experimental protocol**.

> None of the experiments reported in this section appears to have been carried out using blinded experimental protocols, and there has been considerable criticism of the lack of precision of some methods and the lack of consistent internal or external controls in many of the gene-expression experiments ... (NRC, p. 65).
>
> This study did not follow scientifically accepted test guidelines, and the data are of little value in evaluating biologic effects of magnetic fields (NRC 1997, p. 88). [Yet this paper passed their screening process for inclusion, see section on information.]

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> One strength of the study is that the animals served as their own controls; that strength, however, also led to a major shortcoming — the control and experimental periods obviously were not simultaneous. (NRC, p. 102). (How can it be simultaneous!)
>
> No pituitary-adrenal function measurements were included to verify whether the field-exposed rats were actually stressed. (NRC, p. 104).

(8) but **other factors** may have affected the results.

> Whether any of those factors confounded the outcome of the Yellon studies remains unknown. (NRC, p. 101).

These comments may very well be valid but they were expressed so frequently whenever a biological response was reported that I got a definite impression of bias, especially since the studies that showed no biological effects were not similarly scrutinized.

The mandate of the NRC Report, was to determine the bioeffects of residential fields. In the executive summary there is no mention of occupational EMF exposure despite the fact that there is an excellent summary of recent research within the Epidemiological section on pages 179–181. The following are quotes from this summary that indicate increased risk of cancer associated with occupational exposure to electromagnetic fields, none of which appears in the executive summary. This is an example of bias (in favor of no effect) or a limited interpretation of the mandate.

> Across a wide range of geographic settings ... and diverse study designs... workers engaged in electrical occupations have often been found to have slightly increased risks of leukemia and brain cancer (Savitz and Ahlbom 1994) (NRC, p. 179).
>
> Matanoski et al. (1993) ... found little support for increased risk due to increased average fields, but increasing field levels at peak exposure were associated with increased leukemia risk (NRC, p. 180).
>
> Floderus et al. (1993) ... the most highly exposed workers were estimated to have a 3-fold increased risk of chronic lymphocytic leukemia and a 1.6-fold increased risk of total leukemia. Brain-tumor was increased by a factor of 1.5 in the highest category (NRC, p. 180).
>
> ... a large well-designed study of utility workers in Canada and France provided evidence of a 2- to 3-fold increased risk of acute myeloid leukemia among men with increased magnetic field exposure (Theriault et al. 1 994) . Brain cancer showed much more modest increases (relative risk of 1.5–2.8) with increased magnetic field exposure (NRC, p. 180).
>
> Savitz and Loomis (1995) ... Leukemia mortality was not found to be associated with indices of magnetic-field exposure, whereas brain-cancer mortality was associated. Brain cancer mortality generally was found to increase in relation to accumulative exposure, reaching a relative risk of 2.3–2.5 in the most highly exposed workers (NRC, p. 180).
>
> All three studies found no evidence of confounding by the presence of workplace chemicals (NRC, p. 180).
>
> A series of three studies reported an association between electrical occupations and male breast cancer (Tynes and Andersen 1990; Matanoski et al. 1991; Demers et al. 1991) ... (NRC, p. 181).
>
> Female breast cancer in relation to electrical occupations was evaluated by Loomis et al. 1994 ... a modest increase in risk was found for women in electrical occupations, particularly telephone workers ... (NRC, p. 181).
>
> The relative risks in the upper categories of 2–3 reported in the high quality studies of Floderus et al. 1993 and Theriault et al. 1994 cannot be ignored (NRC, p. 181). Yet this

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is exactly what the NRC report did ... it ignored some vital pieces of information in its executive summary.

8.2. The question of consistency

The issue of “consistency” vs. “inconsistency” is an interesting one. For example, water boils at 100°C but it can also boil at higher and lower temperatures depending on atmospheric pressure. Without our understanding of the importance of atmospheric pressure we may claim that two studies — each of which report a different temperature for the boiling point of water — are inconsistent. It is not until we understand the role atmospheric pressure plays that we recognize the consistency.

Similarly in EMF research, we can state that a study showing the link between cancer and residential or occupational EMF exposure and that showing a link between bone healing and medical EMF exposure are inconsistent because one is linked with a harmful cancerous growth and the other with a beneficial growth of new bone . However, if the underlying mechanism is similar, namely that electromagnetic fields enhance the rate of cell division (and (or) cell differentiation) then we again recognize the consistency.

Not all studies found an increased relative risk (odds ratio) between residential EMF exposure and one specific type of childhood cancer. Some found an increase in acute myeloid leukemia, others in lymphomas, and still others in central nervous system tumors. Once again, this can be viewed as an inconsistency. Alternatively, if EMFs are involved in cancer promotion rather than cancer initiation (which is what the in vivo studies tend to show), then the cancer type is not necessarily an inconsistency. The higher relative risk for different types of cancer may be viewed as a consistency if EMF promotes tumor growth that was initiated by a different agent. The type of cancer would be agent (or initiator) specific. Furthermore, an underlying mechanism that supports cancer promotion (of several cancer types) is the melatonin hypothesis.

8.3. Classical chemical toxicology and electric and magnetic field exposure

Some of the apparently contradictory results may be because the chemical toxicology model, with its emphasis on dose/response, may be the wrong model for electromagnetic bioeffects. We may be getting a distorted picture by viewing the results through this lens. Frey (1994) suggests that the radio, with its frequency modulated carrier waves, may provide a much better model for understanding electromagnetic bioeffects. The radio picks up a very weak electromagnetic signal and converts it into sound. The electromagnetic energies that interfere with the radio signal are not necessarily those that are the strongest but rather those that are tuned to the same frequencies or modulations. Similarly “if we impose a weak electromagnetic signal on a living being, it may interfere with normal function if it is properly tuned” (Frey 1994). This makes sense once we recognize that living organisms generate and use low frequency electromagnetic fields in everything from cellular regeneration through cellular communication to nervous system function. Frey goes on to suggest that high frequency electromagnetic waves may carry low frequency electromagnetic signals to the cell.

9. Conclusions

The debates and discussions we are having as a society about electromagnetic fields are no different to those that occurred with asbestos, lead, DDT, and acid rain. All of these issues had their experts who stated that the result were inconclusive or contradictory or unproven until the mechanisms were identified.

The arguments presented by physicists are compelling and I find myself questioning the data and my growing belief that low frequency EMF can affect biota. When data and theory do not coincide where do you look for answers? Frey (1994) addresses this question.

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> This area of biological research has its “naysayers” ... who imagine they possess the real truth. They like to talk about the dogma, “the laws of physics.” If the data do not conform to the dogma then the data must be wrong.
>
> But one does not challenge data with the current dogma ... It is the dogma that is tested by data obtained with constantly increasing precision of measurement and observation ... This is the great leap of thinking that created Science out of the thinking in the Medieval Age. It is to be expected that theories conceived at one level of observation will have to be modified as observational ability improves. This is what some scientists ignore. They implicitly assume that they have reached a “fundamental” level of understanding, which leaves no room for even more fundamental levels of understanding.

After several years of trying to make sense of data from diverse fields I have become increasingly convinced that electric and magnetic fields do affect living systems; that these effects depend on individual sensitivity; that they vary with geography, as influenced by the earth’s magnetic field, and with daily and seasonal cycles; that they can occur at low frequencies and low intensities; and that we are very close to understanding several of the mechanisms involved.

If we wish to manage the risk of EMF we need to understand the parameters of exposure that are biologically important (this has yet to be done) and to identify biological end points and the mechanisms responsible for those endpoints. Much scientific work still needs to be done but this should not delay policy makers who are now in a position to introduce cost-effective, technologically feasible measures to limit EMF exposure.

The entire realm of EMF interactions with living organisms is complex, but I am convinced that studies in this area will provide us with a novel view of how living systems work and, in the process, will open a new dimension into scientific exploration dealing with living energy systems. I am also convinced that this information will have many beneficial outcomes. We will better understand certain disorders and will learn to treat these and other ailments, for which we currently lack the tools. Once the regulators, producers, and users of this technology recognize that electromagnetic fields can have positive and negative bioeffects, that we can enhance or minimize these effects at will, and that properly executed research in this area is neither a threat nor a liability to the industry, then we will begin to make major new advances in this important area of study.

Acknowledgements

This work was completed during a sabbatical at Trent University. I would like to thank my colleagues in the Physics Department, particularly John Earnshaw and Keith De’Bell, for our discussions about electromagnetism; the members of the Energy Fields Working Group for introducing me to the health benefits of energy fields; students in my BEEF course (Biological Effects of Electromagnetic Fields); and Malcolm Hutchinson for holding a fluorescent tube under a powerline and sparking my interest in this field.

References

Adey, W.R. 1980. Frequency and power windowing in tissue interactions with weak electromagnetic fields. IEEE, **68**: 119–125.

Afzal, S.M.J., and Liburdy, R.P. 1998. Magnetic fields reduce the growth inhibitory effects of tamoxifen in a human brain tumor cell line. *In* Electricity and magnetism in biology and medicine. *Edited by* F. Bersani. Plenum Press, Bologna, Italy.

Ahlbom, A., Feychting, M., and Koskenvuo, M. 1993. Electromagnetic fields and childhood cancer (letter). Lancet, **342**: 1295–1296.

Andrienko, L.G. 1977. The effect of an electromagnetic of industrial frequency on the generative function in an experiment (in Russian). Gig. Sanit. **6**: 22–25; Engl. Transl. Gig. Sanit. **7**: 27–31.

Baker, R.R., Mather, J.G., and Kennaugh, J.H. 1983. Magnetic bones in human sinuses. Nature, **301**: 78–80.

©2000 NRC Canada

Bassett, C.A.L. 1995. Bioelectromagnetics in the service of medicine. *In* Electromagnetic fields: Biological interactions and mechanisms. *Edited by* M. Blank. American Chemical Society, Washington, D.C. pp. 262–275.

Baum, A., Mevissen, M., Kamino, K., Mohr, U., and Loscher, W. 1995. A histopathological study of alternations in DMBA-induced mammary carcinogenesis in rats with 50 Hz, 100 μT magnetic field exposure. Carcinogenesis, **16**: 119–125.

Bawin, S.M., and Adey, W.R. 1976. Sensitivity of calcium binding in cerebral tissue to weak environmental electric fields oscillating at low frequency. Proc. Natl. Acad. Sci. U.S.A. **73**: 1999.

Beason, R.C., and Nichols, J.E. 1984. Magnetic orientation and magnetically sensitive material in a transequatorial migratory bird. Nature, **309**: 151–153.

Bedford, P.J., and Ridge, J. 1999. Siting of wireless telecommunications antennae, urban planning and development services. City of Toronto Staff Report, Dec. 6, 1999, Toronto, Ont. 20 pp.

Beniashvili, D.S., Beniashvili, V.G., and Menabde, M.Z. 1991. Low-frequency electromagnetic radiation enhances the induction of rat mammary tumors by nitrosomethyl urea. Cancer Lett. **61**: 75–79.

Bennett, W.R., Jr. 1994. Health and low-frequency electromagnetic fields. Yale University Press, New Haven, Conn. 189 pp.

Berkow, R., Beers, M.H., and Fletcher, A.J. 1997. The Merch manual of medical information. Merch and Co., Inc., Whitehouse Station, N.J. pp. 402–410.

Blackman, C.F., Elder, J.A., Weil, C.M., Benane, S.G., Eichinger D.C., and House, D.E. 1979. Induction of calcium-ion efflux from brain tissue by radio-frequency radiation: Effects of modulation frequency and field strength. Radio Sci. **14**: 93.

Blackman, C.F., et al. 1985. Effects of ELF (1–120 Hz) and modulated (50 Hz) RF fields on the efflux of calcium ions from brain tissue in vitro. Bioelectromagnetics, **6**: 1–11.

Blackman, C.F., Blanchard, J.P., Benane, S.G., and House, D.E. 1994. Empirical test of an ion parametric resonance model for magnetic field interactions with PC-12 cells. Bioelectromagnetics, **15**: 239–260.

Blakemore, R. 1975. Magnetotactic bacteria. Science, **190**: 377–379

Breck-Friis, J., Kjellman, B.F., and Wetterberg, L. 1985. Serum melatonin in relation to clinical variables in patients with major depressive disorder and a hypothesis of a low melatonin syndrome. Acta Psychiatr. Scand. **71**: 319–330.

Brodeur, P. 1993. The great power-line cover-up. Little, Brown and Company (Canada) Limited, 326 pp.

Bunin, G.R., Ward, E., Kramer, S., Rhee, C.A., and Meadows, A.T. 1990. Neuroblastoma and parental occupation. Am. J. Epidemiol. **131**: 776–780.

Cantor, K.P., Dosemeci, M., Brinton, L.A., and Stewart, P.A. 1995. Re Breast cancer mortality among female electrical workers in the United States (letter). J. Natl. Cancer Inst. **87**: 227–228.

Chatterjee, I., Wu, D., and Gandhi, O.P. 1986. Human body impedance and threshold currents for perception and pain for contact hazard analysis in the VLF-MF band. IEEE Trans. Biomed. Eng. BME-**33**: 486–494.

Cohen, D. 1975. Measurements of the magnetic fields produced by the human heart, brain, and lungs. IEEE Trans. Magnet. MAG-**11**(2): 694–705.

Coleman, M., Bell, C.M.J., Taylor H.L., and Primic-Zakelj, M. 1989. Leukaemia and residence near electricity transmission equipment: A case-control study. Br. J. Cancer, **60**: 793–798.

Coogan, P.F., Clapp, R.W., Newcomb, P.A., Wenzl, T.B., Bogdan, G., Mittendorf, R., Baron, J.A., and Longnecker, M.P. 1996. Occupational exposure to 60-hertz magnetic fields and risk of breast cancer in women. Epidemiology, **7**: 459–464.

Day, N. 1999. Exposure to power-frequency magnetic fields and the risk of childhood cancer. Lancet, **354**: 1925–1931.

DeMatteo, B. 1986. Terminal shock: The health hazards of video display terminals. NC Press Ltd., Toronto, Ont. 239 pp.

Demers, P.A., Thomas, D.B., Rosenblatt, K.A, and Jimenez, L.M. 1991. Occupational exposure to electromagnetic fields and breast cancer in men. Am. J. Epidemiol. **134**: 340–347.

Dubrov, A.P. 1978. The geomagnetic field and life: Geomagnetobiology. *Translated from Russian by* F.L. Sinclair. Plenum Press, N.Y. 318 pp.

Dutta, S.K., Ghoshn, B., and Blackman, C.F. 1989. Radiofrequency radiation-induced calcium ion efflux enhancement from human and other neuroblastoma cells in culture. Bioelectromagnetics, **10**: 197–202.

Ekstrom, T., Mild, K.H., and Homberg, R. 1998. Mammary tumours in Sprague-Dawley rats after initiation of

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DMBA followed by exposure to 50 Hz electromagnetic fields in a promotional scheme. Cancer Lett. **123**: 107–111.

EMF Rapid. 1996. Questions and answers: EMF in the workplace. National Institute for Occupational Safety and Health, National Institute of Environmental Health Sciences, US Department of Energy, DOE/GO-10095-218, DE95013123.

EPA. 1992. EMF in your environment: Magnetic field measurements of everyday electrical devices. EPA/402/R-92/008. Office of Radiation and Indoor Air, US Environmental Protection Agency, Washington, D.C.

EPRI. 1993. Survey of residential magnetic field sources: Goals, results and conclusions, Vol. 1. Project RP3335-02. Rep. TR-102759-V1. *Prepared by* High voltage Transmission Research Center *for* Electric Power Research Institute, Palo Alto. Calif.

Fews, A.P., Henshaw, D.L., Keitch, P.A., Close, J.J., and Wilding, R.J. 1999. Increased exposure to pollutant aerosols under high voltage power lines. Int. J. Radiat. Biol. **75**(12): 1505–1521.

Feychting, M., and Ahlborm, A. 1993. Magnetic fields and cancer in children residing near Swedish high-voltage power lines. Am. J. Epidemiol. **138**: 467–481.

Feychting, M., Chulgen, G., Olsen, J.H., and Ahlbom, A. 1995. magnetic fields and childhood cancer — a pooled analysis of two Scandinavian studies. Eur. J. Cancer, **31**(A): 2035–2039.

Feychting, M., Forssen, U., and Floderus, B. 1997. Occupational and residential magnetic field exposure and leukemia and central nervous system tumors. Epidemiology, **8**: 384–389.

Floederus, B., Persson, T., Stenlund, C., Wennberg, W., Ost, A., and Knave, B. 1993. Occupational exposure to electromagnetic fields in relation to leukemia and brain tumors: a case-control study in Sweden. Cancer Causes Control **4**: 465–476.

Floderus, B., Tornqvist S., and Stenlund, C. 1994. Incidence of selected cancers in Swedish railway workers, 1961–79. Cancer Causes Control, **5**: 189–194.

Free, M.J., Kaune, W.T., Phillips, R.D, and Cheng, H.C. 1981. Endocrinological effects of strong 60-Hz electric fields on rats. Bioelectromagnetics, **2**: 105–121.

Frey, A.H. 1967. Brain stem evoked responses associated with low-intensity pulsed UHF energy. J. Appl. Physiol. **23**: 984–988.

Frey, A.H. 1994. On the nature of electromagnetic field interactions with biological systems. R.G. Landes Co., Austin, Tex. 211 pp.

Fulton, J.P., Cobb, S., Preble, L., Leone, L., and Formann, E. 1980. Electrical wiring configuration and childhood leukemia in Rhode Island. Am. J. Epidemiol. **111**: 292–296.

Goldhaber, M.K., Polen, M.R., and Hiatt, R.A. 1988. The risk of miscarriage and birth defects among women who use visual display terminals during pregnancy. Am. J. Ind. Med. **13**: 695–706.

Goldsmith, J.R. 1995. Epidemiological evidence of radio frequency radiation (microwave) effects on health in military, broad-casting, and occupational studies. Int. J. Occup. Environ. Health, **1**: 47–57.

Gould, J.L., Kirschvink, J.L., and Deffeyes, K.S. 1978. Bees have magnetic remanence. Science, **201**: 1026–1028.

Green, L.M., Miller, A.B., Agnew, D.A., Greenber, M.L., Li, J., Villeneuve P.J., and Tibshirani, R. 1999. Childhood leukemia and personal monitoring of residential exposures to electric and magnetic fields in Ontario, Canada. Cancer Causes Control, **10**: 233–243.

Guenel, P., Raskmark, P., Andersen, J.B., and Lynge, E. 1993. Incidence of cancer in persons with occupational exposure to electromagnetic fields in Denmark. Br. J. Ind. Med. **50**: 758–764.

Hansen, T., Bratlid, T., and Brenn, T. 1987. Midwinter insomnia in the subarctic region: Evening levels of serum melatonin and cortisol before and after treatment with bright artificial light. Acta Psychiatr. Scand. **75**: 428–434.

Harland, J.D., and Liburdy, R.P. 1997. Environmental magnetic fields inhibit the antiproliferative action of tamoxifen and melatonin in a human breast cancer cell line. Bioelectromagnetics, **18**: 555–562.

Harland, J.D., Levine G.A., and Liburdy, R.P. 1998. Differential inhibition of tamoxifen's oncostatic functions in a human breast cancer cell line by a 12 mG (1.2 μT) magnetic field. *In* Electricity and magnetism in biology and medicine. *Edited by* F. Bersani. Plenum Press, Bologna, Italy.

Harrington, J.M., McBridge, D.I., Sorahan, T., Paddle, G.M., and van Tongeren, M. 1997. Occupational exposure to magnetic fields in relation to mortality from brain cancer among electricity generation and transmission workers. Occup. Environ. Med. **54**: 7–13.

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Hatch, E.E., Linet, M.S., Kleinerman, R.A., Tarone, R.E., Severson, R.K., Hartsoek, C.T., Haines, C., Kaune, W.T., Friedman, D., Robison, L.L., and Wacholder, S. 1998. Association between childhood acute lymphoblastic leukemia and use of electric appliances during pregnancy and childhood. Epidemiology, **9**: 234–245.

Havas, M., Hutchinson, T.C., and Likens, G.E. 1984. Red herrings in acid rain research. Environ. Sci. Technol. **18**: 176A–186A.

Hitchcock, T.T., and Patterson, R.M. 1995. Radio-frequency and ELF electromagnetic energies: A handbook for health professionals. Van Nostrand Reinhold, N.Y., 542 pp.

Hsu, C., and Li, C., 1994. Magnetoreception in Honeybees. Science, **265**: 95–96.

Johansen, C., and Olsen, J. 1998. Risk of cancer among Danish utility workers — A nationwide cohort study. Am. J. Epidemiol. **147**: 548–555.

Johnson, C.C., and Spitz, M. 1989. Childhood nervous system tumours: An assessment of risk associated with paternal occupations involving use, repair or manufacture of electrical and electronic equipment. Int. J. Epidemiol. **18**: 756–762.

Jones, D.S., and MacFadden, B.J. 1982. Induced magnetization in the monarch butterfly, *Danaus plexippus*. J. Exp. Biol. **96**: 1–9.

Kappenman, J.G. 1996. Lessons learned from solar cycle 22 and outlook for solar cycle 23. "http: //www.mpelectric.com/storms/," last modified 12/17/96. pp. 5.

Katsir, G., Baram, S., and Parola, A. 1998. Effect of sinusoidally varying magnetic fields on cell proliferation and adenosine-deaminase specific activity. Bioelectromagnetics, **19**: 46–51.

Kavaliers, M., and Ossenkopp, K. 1994. Effects of magnetic and electric fields in invertebrates and lower vertebrates. *In* Biological effects of electric and magnetic fields: Sources and mechanisms. Vol. 1. *Edited by* D.O. Carpenter and S. Ayrapetyan, Academic Press, N.Y., pp. 205–240.

Keeton, W.T. 1991. Proc. Natl. Acad. Sci. **68**: 102.

Kheifet, L., Afifi, A.A., Buffler, P., Zhang, Z., and Matkin, C. 1997. Occupational electric and magnetic field exposure and leukemia. J. Occup. Environ. Health, **39**: 1074–1091.

Kholodov, Yu.A., Kozlov A.N., and Gorbach, A.M. 1990. Magnetic fields of biological objects. The USSR Academy of Sciences, Institute of Higher Nervous Activity and Neurophysiology. Translated from Russian by A.N. Tarus. Nauka Publishers, Moscow.

Kirschvink, J.L., Jones D.S., and MacFadden, B.J. (*Editors*). 1985. Magnetite biomineralization and magnetoreception in organisms: A new biomagnetism. Vol. 5, Topics in Geobiology. Plenum Press, N.Y.

Korobkova, V.P., Morozov, Yu.A., Stolarov, M.D., and Yakub, Yu.A. 1972. Influence of the electric field in 500 and 750 kV switchyards on maintenance staff and means for its protection. *In* International Conference on Large High Voltage Electric Systems, Paris, August 1972, CIGRE, Paris 1977.

Kulczycki, J. 1989. Basis of electromagnetic hygiene. The Planetary Association for Clean Energy, Inc., Ottawa, Canada, 75 pp.

Larkin, R.P., and Sutherland, R.J. 1977. Migrating birds respond to Project Seafarer's electromagnetic field. Science, **195**: 777–779.

Levitt, B.B. 1995. Electromagnetic fields: A consumer's guide to the issues and how to protect ourselves. Harcourt Brace and Company, San Diego, Calif., 432 pp.

Lewy, A.J., Kern, H.A., Rosenthal, N.E., and Wehr, T.A. 1982. Bright artificial light treatment of a manic-depressive patient with a seasonal mood cycle. Am. J. Psychiatr. **139**(11): 1496–1498.

Liboff, A.R. 1985. Geomagnetic cyclotron resonance in living cells. J. Biol. Phys. **13**: 99–102.

Liboff, A.R., Williams, T., Jr., Strong, D.W., and Wistar, R., Jr. 1984. Time-varying magnetic fields: Effect on DNA synthesis. Science, **223**: 818–820.

Liburdy, R.P., Sloma, T.R., Sokolic, R., and Vaswen, P. 1993. ELF magnetic fields, breast cancer and melatonin: 60 Hz fields block melatonin's oncostatic action on ER positive breast cancer cell proliferation. J. Pineal Res. **14**: 89–97.

Lin, R.S., Dischinger, P.C., Conde, J., and Farrell, K.P. 1985. Occupational exposure to electromagnetic fields and the occurrence of brain tumors. J. Occup. Med. **27**: 413–419.

Linet, M.S., Hatch, E.E., Kleinerman, R.A., Robison, L.L., Kaune, W.T., Friedman, D.R., Severson, R.K., Haines, C.M., Hartsock, C.T., Niwa, S., Wacholder, S., and Tarone, R.E. 1997. Residential exposure to magnetic fields and acute lymphoblastic leukemia in children. New Engl. J. Med. **337**: 1–7.

Litovitz, T.A., Krause, D., and Mullins, J.M. 1991. Effect of coherence time of the applied magnetic field on

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ornithine decarboxylase activity. Biochem. Biophys. Res. Comm. **178**: 862–865.
London, S.J., Thomas, D.C., Bowman, J.D., Sobel, E., Cheng, T.-C, and Peters, J.M. 1991. Exposure to residential electric and magnetic fields and risk of childhood leukemia. Am. J. Epidemiol. **134**: 923–937.
London, S.J., Bowman, J.D., Sobel, E., Thomas, D.C., Garabrant, D.H., Pearce, N., Bernstein L., and Peters, J.M. 1994. Exposure to magnetic fields among electrical workers in relation to leukemia risk in Los Angeles County. Am. J. Ind. Med. **26**: 47–60.
Loomis, D.P. 1992. Cancer of breast among men in electrical occupations (letter). Lancet, **339**: 1482–1483.
Loomis, D.P., Savitz, D.A., and Ananth, C.V. 1994. Breast cancer mortality among female electrical workers in the United States. J. Natl. Cancer Inst. **86**: 921–925.
Loscher, W., Wahnschaffe, U., Mevissen, M., Lerchl, A., and Stamm, A. 1994. Effects of weak alternating magnetic fields on nocturnal melatonin production and mammary carcinogenesis in rats. Oncology, **51**: 288–295.
Loscher, W., Mervissen, M., Lehmacher, W., and Stamm, A. 1993. Tumor promotion in a breast cancer model by exposure to weak alternating magnetic field. Cancer Lett. **71**: 75–81.
Marino, A.A. 1988. Environmental electromagnetic energy and public health. *In* Modern bioelectricity. *Edited by* A.A. Marino. Dekker, New York, N.Y.
Matanoski, G.M., Breysse, P.N., and Elliott, E.A. 1991. Electromagnetic field exposure and male breast cancer, Lancet, **337**: 737.
Matanoski, G.M., Elliott, E.A., Breysse, P.N., and Lynberg, M.C. 1993. Leukemia in telephone lineman. Am. J. Epidemiol. **137**: 609–619.
Mather, J.G., and Baker, R.R. 1981. Magnetic sense of direction in woodmice for route-based navigation. Nature, **291**: 152–155.
McBride, M.L., Gallagher, R.P., Theriault, G., Armstrong, B.G., Tamaro, S., Spinelli, J.J., Deadman, J.E., Fincham, S., Robson, D., and Choi, W. 1999. Power-frequency electric and magnetic fields and risk of childhood leukemia in Canada. Am. J. Epidemiol. **149**: 831–842.
Meinert, R., and Michaelis, J. 1996. Meta-analysis of studies on the association between electromagnetic fields and childhood cancer. Radiat. Environ. Biophys. **35**: 11–18.
Mevissen, M., Lerchl, A., Szamel M., and Loscher, W. 1996. 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**: 169–195.
Mevissen, M., Haubler, M., Lerchl, A., and Loscher, W. 1998*a*. Acceleration of mammy tumorigenesis by exposure of 7,12-dimethylbenz(a)anthracene 100 μT magnetic field: replication study. J. Toxicol. Environ. Health, Part A, **53**: 401–418.
Mevissen, M., Haussler, M., Szamel, M., Emmendorffer, A., Thun-Battersby, S., and Loscher, W. 1998*b*. Complex effects of long-term 50 Hz magnetic field exposure *in vivo* on immune functions in female Spragu-Dawley rats depend on duration of exposure. Bioelectromagnetics, **19**: 259–270.
Michaelis, J.J., Schuz, H., Meinert, R., Menger, M., Grigat, J.P., Kaatsch, P., Kalestsch, U., Miesner, A., Stamm, A, Brinkmann K., and Karner, H. 1997. Childhood leukemia and electromagnetic fields: Results of a population-based case-control study in Germany. Cancer Causes Control, **8**: 167–174.
Michaelis, J., Schuz, H., Meinert, R., Zenmann, E., Grigat, J.-P., Kaatsch, P., Kaletsch, U., Miesner, A., Brinkmann, K., Kalkner W., and Karner, H. 1998. Combined risk estimates for two German population-based case-control studies on residential magnetic fields and childhood acute leukemia. Epidemiology, **9**: 92–94.
Milburn, M., and Oelbermann, M. 1994. Electromagnetic fields and your health. New Star Books, Vancouver, B.C. 207 p.
Miller, A.B., To, T., Agnew, D.A., Wall, C., and Green, L.M. 1996. Leukemia following occupational exposure to 60 Hz electric and magnetic fields among Ontario electricity utility workers. Am. J. Epidemiol. **144**: 150–160.
Miyakoshi, J., Ohtsu, S., Shibata, T., and Takebe, H. 1996. Exposure to magnetic field (5 mT at 60 Hz) does not affect cell growth and c-myc gene expression. J. Radiat. Res. **37**: 185–191.
Miyakoshi, J., Mori, Y., Yamagishi, N., Yagi K., and Takebe, H. 1998. Suppression of high-density magnetic field (400 mT at 50 Hz)-induced mutations by wild-type p53 expression in human osteosarcoma cells. Biochem. Biophys. Res. Comm. **243**: 579–584.
Nasca, P.C., Baptiste, M.S., MacCubbin, P.A., Metzger, B.B., Carlton, K., Greenwald, P., Armbrustmacher,

©2000 NRC Canada

V.W., Earle K.M., and Waldman, J. 1988. An epidemiologic case-control study of central nervous system tumors in children and parental occupational exposures. Am. J. Epidemiol. **128**: 1256–1265.

National Energy Board. 1991. Canadian energy supply and demand 1990–2010. Calgary. (as cited in The State of Canada's Environment 1991.)

Nordenson, I., Hansoon Mild, K., Nordstrom, S., Sweins, A., and Birke, E. 1984. Clastogenic effects in human lymphocytes of power frequency electric fields: In vivo and in vitro studies. Radiat. Environ. Biophys. **23**: 191–201.

Nordenson, I., Hansson Mild, K., Anderson, G., and Sandstrom, M. 1994. Chromosomal aberrations in human amniotic cells after intermittent exposure to fifty hertz magnetic fields. Bioelectromagnetics, **15**: 293–301.

Nordstrom, S., Birke, E., and Gustavsson, L. 1983. Reproductive hazards among workers at high voltage substations. Bioelectromagnetics, **4**: 91–101.

NRC. 1997. Possible health effects of exposure to residential electric and magnetic fields, National Research Council (U.S.) Committee on the Possible Effects of Electromagnetic Fields on Biologic Systems. National Academy Press, Washington D.C. 356 pp.

NRPB. 1992. Electromagnetic fields and the risk of cancer: Report of an advisory group on non-ionising radiation. Vol 3(1). Documents of the National Radiation Protection Board: Oxon.

NTP. 1998. Studies of magnetic field promotion in Sprague-Dawley rats. US Department of Health and Human Services, Public Health Service, National Institute of Environmental Health Sciences, National Toxicology Program, Research Triangle Park, N.C.

Ogura, M., Kato, M., Arai, N., Sasada, T., and Sakaki, Y. 1992. Magnetic particles in Chum Salmon: extraction and transmission microscopy. Can. J. Zool. **70**: 874–877.

Olsen, J.H., Nielsen, A., and Schulgen, G. 1993. Residence near high voltage facilities and risk of cancer in children. Br. Med. J. **307**: 891–895.

Ouellet-Hellstrom, R., and Stewart, W.F. 1993. Miscarriages among female physical therapists who report using radio- and microwave-frequency electromagnetic radiation. Am. J. Epidemiol. **138**: 775–786.

Poole, C., Kavet, R., Funch, D.P., Donelan, K., Charry, J.M., and Dreyer, N.A. 1993. Depressive symptoms and headaches in relation to proximity of residence to an alternating-current transmission line right-of-way. Am. J. Epidemiol. **137**: 318–330.

Portier, C.J, and Wolfe, M.S. (*Editors*). 1997. EMF Science Review Symposium Breakout Group Reports for In Vivo Laboratory Research Findings. Research Triangle Park, N.C. National Institute of Environmental Health Sciences, Durham, N.C.

Portier, C.J, and Wolfe, M.S. (*Editors*). 1998*a*. EMF Science Review Symposium Breakout Group Reports for Epidemiological Research Findings. Research Triangle Park, N.C. National Institute of Environmental Health Sciences, San Antonio, Tex.

Portier, C.J, and Wolfe, M.S. (*Editors*). 1998*b*. EMF Science Review Symposium Breakout Group Reports for Clinical and In Vivo Laboratory Research Findings. Research Triangle Park, N.C. National Institute of Environmental Health Sciences, Phoenix, Ariz.

Portier, C.J, and Wolfe, M.S. (*Editors*). 1998*c*. Assessment of health effects from exposure to power-line frequency electric and magnetic fields. National Institute of Environmental Health Sciences Working Group Report of the National Institutes of Health. NIH Publication No. 98-3981, Research Triangle Park, N.C. 508 pp.

Presman, A.S. 1970. Electromagnetic fields and life. Plenum Press, New York, N.Y. 336 pp.

Preston-Martin, S., Gurney, J.G., Pogoda, J.M., Holly, E.A., and Mueller, B.A. 1996*a*. Brain tumor risk in children in relation to use of electric blankets and water bed heaters. Results from the United States west coast childhood brain tumor study. Am. J. Epidemiol. **143**: 116–1122.

Preston-Martin, S., Navidi, W., Thomas, D., Lee, P.-J., Bowman, J., and Pogoda, J. 1996*b*. Los Angeles study of residential magnetic fields and childhood brain tumors. Am. J. Epidemiol. **143**: 105–119.

Rea, W.J., Pan, Y., Fenyves, E.J., Sunisawa, I., Suyama, H., Samadi, N., and Ross, G.H. 1991. Electromagnetic field sensitivity. J. Bioelectr. **10**: 241–256.

Reichmanis, M., Perry, F.S., Marino, A.A., and Becker, R.O. 1979. Relation between suicide and the electromagnetic field of overhead power lines. Chem. Phys. **11**: 395–403

Reiter, R.J., and Robinson, J. 1995. Melatonin: your body's natural wonder drug. Bantam Books, New York, N.Y., 290 pp.

Reiter, R.J., Melchiorri, D., Sewerynek, E., Poeggler, B., Barlow-Walder, L.R., Chuang, J.I., Ortiz, G.G., and

©2000 NRC Canada

Acuna-Castroviejo, D. 1995. A review of the evidence supporting melatonin's role as an anti-oxidant. J. Pineal Res. **18**: 1–11.
Riley, K. 1995. Tracing EMFs in building wiring and grounding. Magnetic Sciences International, Tucson, Ariz. 126 pp.
Rosenbaum, P.F., Vena, J.E., Zielezny, M.A., and Michalek, A.M. 1994. Occupational exposures associated with male breast cancer. Am. J. Epidemiol. **139**: 30–36.
Royal Society of Canada. 1999. A review of the potential health risks of radiofrequency fields from wireless telecommunication devices. RSC.EPR 99-1, 146 pp.
Sahl, J.D., Kelsh M.A., and Greenland, S. 1993. Cohort and nest case-control studies of hematopoietic cancers and brain-cancer among electric utility workers. Epidemiology, **4**: 104–114.
Savitz, D.A., and Ahlbom, A. 1994. Epidemiologic evidence on cancer in relation to residential and occupational exposures. *In* Biological effects of electric and magnetic fields: sources and mechanisms Vol. 1. *Edited by* D.O. Carpenter and S. Ayrapetyan, Academic Press, N.Y., pp. 233–261.
Savitz, D.A., and Calle, E.E. 1987. Leukemia and occupational exposure to electromagnetic fields: Review of epidemiological surveys. J. Occup. Med. **29**: 47–51.
Savitz, D.A., and Loomis, D.P. 1995. Magnetic field exposure in relation to leukemia and brain cancer mortality among electric utility workers. Am. J. Epidemiol. **141**: 123–134.
Savitz, D.A., Wachtel, H., Barnes, F.A., John, E.M., and Tvrdik, J.G. 1988. Case-control study of childhood cancer and exposure to 60 Hz magnetic fields. Am. J. Epidemiol. **128**: 21–38.
Savitz, D.A., John, E.M., and Kleckner, R.C. 1990. Magnetic field exposure from electric appliances and childhood cancer. Am. J. Epidemiol. **131**: 763–773.
Severson, R.K., Stevens, R.G., Kaune, W.T., Thomas, D.B., Heuser, L., Davis, S., and Sever, L.E. 1988. Acute nonlymphocytic leukemia and residential exposure to power frequency magnetic fields. Am. J. Epidemiol. **128**: 10–20.
Shandala, M.G., Dumanskiy, Yu.D., and Bezdol'naya, I.S. 1986. The biological effects of power-frequency electric fields in the environment. Translated from Russian by C.H. Dodge and B.J.B Dodge.
Sobel, E., Davanipour, Z., Sulkava, R., Erkinjuntti, T., Wikstrom, J., Henderson, V.W., Buckwalter, G., Bowman, J.D., and Lee. P-J. 1995. Occupations with exposure to electromagnetic fields: A possible risk factor for Alzheimer's disease. Am. J. Epidemiol. **142**(5): 515–523
Spitz, M.R., and Johnson, C.C. 1985. Neuroblastoma and paternal occupation, a case-control analysis. Am. J. Epidemiol. **121**: 924–929.
Steneck, N.H. 1984. The microwave debate. MIT Press, Cambridge, U.K., 279 pp.
Stevens, R.G. 1987*a*. Electric power use and breast cancer: A hypothesis. Am. J. Epidemiol. **125**: 294–300.
Stevens, R.G. 1987*b*. Electric power use and breas cancer. Am. J. Epidemiol. **125**: 556–561.
Sulman, F.G. 1980. The effect of air ionization, electric fields, atmospherics and other electric phenomena on man and animals. Charles C. Thomas Publishers, Springfield, Ill. 398 pp.
Sun, W.Q., Heroux, P., Clifford, T., Sadilek, V., and Hamade, F. 1995. Characterization of the 60 Hz magnetic fields in schools of the Carleton Board of Education. Am. Ind. Hyg. Assoc. J. **56**: 1215–1224.
Szmigielski, S. 1996. Cancer morbidity in subjects occupationally exposed to high frequency (radiofrequency and microwave) electromagnetic radiation. Sci. Total Environ. **180**: 9–17.
Tarone, R.E., Kaune, W.T., Linet, M.S., Hatch, E.E., Kleinerman, R.A., Robison, L.L., Boice J.D., and Wacholder, S. 1988. Residential wire codes: reproducivility and relation with measured magnetic fields. Occup. Environ. Med. **55**: 333–339.
The State of Canada's Environment, 1991. Ministry of Supply and Services Canada. Ottawa, Canada.
Theriault, G., Goldber, M., Miller, A.B., Armstrong, B., Guenel, P., Deadman, J., Imbernon, E., To, T., Chevalier, A., Cyr, D., and Wall, C. 1994. Cancer risks associated with occupational exposure to magnetic fields among electric utility workers in Ontario and Quebec, Canada, and France: 1970–1989. Am. J. Epidemiol. **139**: 550–572.
Tomenius, L. 1986. 50-Hz electromagnetic environment and the incidence of childhood tumors in Stockholm County. Bioelectromagnetics, **7**: 191–207.
Tornqvist, S. 1998. Paternal work in the power industry: Effects on children at delivery. J. Occup. Environ. Med. **40**: 111–117.
Tromp, S.W. (*Editor*). 1974. Progress in biometeorology. Division A: Progress in human biometeorology. The effect of weather and climate on man and his living environment. Vol. 1. Micro-and macro-environments in

©2000 NRC Canada

the atmosphere their effects on basic physiological mechanisms of man. Swets and Zeitlinger, Amsterdam, 412 pp.

Tynes, T., and Andersen, A. 1990. Electromagnetic fields and male breast cancer. Lancet, **336**: 1596.

Tynes, T., and Haldorson, T. 1997. Electromagnetic fields and cancer in children residing near Norwegian high-voltage power lines. Am. J. Epidemiol. **145**: 219–226.

Tynes, T., Andersen, A., and Langmark, F. 1992. Incidence of cancer in Norwegian workers potentially exposed to electromagnetic fields. Am. J. Epidemiol. **136**: 81–88.

US DOT. 1993*a*. Magnetic and electric field testing of the Washington Metropolitan Area Transit Authority (WMATA) metrorail system. Vols. 1 and 2, DOT/FRA/ORD-93/04.I and II. Washington, D.C. US Department of Transportation, NTIS: PB94-102472 and PB94-102480.

US DOT. 1993*b*. Magnetic and electric field testing of the Massachusetts Bay Transportation Authority (MBTA) urban transit system. Vols. 1 and 2, DOT/FRA/ORD-93/05.I and II. Washington, D.C. US Department of Transportation, NTIS: PB93-227619 and PB93-227627.

Verkasalo, P.K., Pukkala, E., Kongisto, M.Y., Valjus, J.E., Jarvinen, P.J., Heikkila, K.V., and Koskenvuo, M. 1993. Risk of cancer in Finnish children living close to power lines. Br. Med. J. **307**: 895–898.

Verkasalo, P.K., Heikkila, K., Pukkala, E., Hongisto, M., Valjus, J., Jarvinen, P., and Koskenvuo, M. 1994. Risk of cancer and exposure to power lines (letter). Br. Med. J. **308**: 1163.

Walcott, C., Gould, J.L., and Kirschvink, J.L. 1979. Pigeons have magnets. Science, **205**: 1027–1029.

Walker, M.M., Kirschvink, J.L., and Dizon, A.E. 1984. A candidate magnetic sense organ in the Yellowfin Tuna, *Thunnus albacares*. Science, **224**: 751–753.

Washburn, E., Orza, M., Berlin, J., Nicholson, W., Todd, A., Frumkin, H., and Chalmers, T. 1994. Residential proximity to electricity transmission and distribution equipment and risk of childhood leukemia, childhood lymphoma, and childhood nervous system tumors: Systematic review, evaluation and meta-analysis. Cancer Causes Control, **5**: 299–309.

Wertheimer, N., and Leeper, E. 1979. Electrical wiring configuration and childhood cancer. Am. J. Epidemiol. **109**(3): 273–284.

Wertheimer, N., and Leeper, E. 1982. Adult cancer related to electrical wires near the home. Int. J. Epidemiol. **11**: 345–355.

Wertheimer, N., and Leeper, E. 1986. Possible effects of electric blankets and heated waterbeds on fetal development. Bioelectromagnetics, **7**: 13–22.

Wertheimer, N., and Leeper, E. 1989. Fetal loss associated with two seasonal sources of electromagnetic field exposure. Am. J. Epidemiol.. **129**: 220–224.

Wetterberg, L., Aperia, B., and Yuwiler, A. 1992. Age, alcoholism and depression are associated with low levels of urinary melatonin. J. Psychiatr. Neurosci. **17**(5): 215–224.

WHO. 1998. 1996 World Health Statistics Annual. World Health Organization, Geneva, Switzerland.

Wilkins, J.R., III, and Hundley, V.D. 1990. Paternal occupational exposure to electromagnetic fields and neuroblastoma in offspring. Am. J. Epidemiol. **131**: 995–1008.

Wilkins, J.R., III, and Koutras, R.A. 1988. Paternal occupation and brain cancer in offspring: A mortality-based case-control study. Am. J. Ind. Med. **14**: 299–318.

Wilkins, J.R., III, and Wellage, L.C. 1996. Brain tumor risk in offspring of men occupationally exposed to electric and magnetic fields. Scand. J. Work Environ. Health, **22**: 339–345.

Wilson, B.W. 1988. Chronic exposure to ELF fields may induce depression. Bioelectromagnetics, **9**: 195–205.

Wilson, B.W., Wright, C.W., Morris, J.E., Buschbom, R.L., Brown, D.P., Miller, D.L., Sommers-Flannigan, R., and Anderson, L.E. 1990. Evidence for an effect of ELF electromagnetic fields on human pineal gland function. J. Pin. Res. **9**: 259–269.

Zoeger, J.J., Dunn, R., and Fuller., M. 1981. Magnetic material in the head of the common Pacific Dolphin. Science, **213**: 892–894.

©2000 NRC Canada