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Introduction

Recently a National Research Council (NRC) panel stated that electromagnetic field (EMF) exposure to anthropogenic sources (e.g., power lines or household electric appliances) poses no significant human health hazard. The panel based its finding on its review of the current body of research of some 500 studies.[1] This finding quickly became widely publicized through many newspaper articles and periodicals.[2] There is no doubt the subject will remain in the public eye, and because some scientists disagree with the panel's findings, EMF exposure will remain on the front burner of scientific investigation and an arena of debate. This paper reviews some important aspects of the EMF controversy.

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1 National Academy Press (visited July 1997) <http://www.nap.edu> (homepage).

2 Sharon Begley, Daniel Glick & Mary Hager, *The Force is With You: Electromagnetic Fields Beat the Rap,* Newsweek, Nov. 11, 1996, at 67; Curt Suplee, *Panel: Power Lines, Disease Not Linked; Rectifying "The Vast Amount of Confusion",* Pittsburgh Post Gazette, Nov. 1, 1996, at A-1, A-7 and Jocelyn Kaiser, *Panel Finds EMFs Pose No Threat,* 274 Science 910 (1996).

Electromagnetic Fields

EMFs surround every electrical device. Anthropogenic EMFs arise from *man-made* sources, e.g., electrical appliances and power lines. Naturally occurring EMFs are associated, for example, with lightning, magnetic ores and electric potentials found in living cells. EMFs are ubiquitous; exposure is inevitable.

Electromagnetic Field Strength as a Function of[3] Distance from Several EMF Sources

EMF Source	Distance (feet)	Strength (mG)
Common [a]		
Microwave Oven	0.5	200
	1.0	4
Vacuum Cleaner	0.5	300
	1.0	60
Power Drill	0.5	150
	1.0	30
Office Copy Machine	0.5	90
	1.0	20
Hair Dryer	0.5	300
	1.0	1
Electric Shaver	0.5	100
	1.0	20
Transmission Lines [b]		
115 kV	0	29.7
	49	6.5
	200	0.4
230 kV	0	57.5
	49	19.5
	200	1.8

3 *a.* Median field strength (milligauss) for typical 60 Hz electric current.

b. The typical power line right-of-way is 49 feet; "0"distance measurements were taken directly below lines of unknown height. Mean field strengths are based on 321 measurements; field strengh may, depending on loads, be twice the mean.

Source of data: U.S. National Inst. of Envtl. Health Sciences & Dep't of Energy, Questions and Answers About EMF Electric and Magnetic Fields Associated with the Use of Electric Power, 38–46 (1995).

Generally, EMFs have separate electric and magnetic components which can be measured. Electric fields are measured as volts per meter (V/m) and are produced by the electric potential — the force that causes current or electron flow in a conductor. Magnetic fields are measured in units of Gauss (G) or Tesla (T) (1 T = 10,000 G) and are produced by current, which is the movement of electrons in a conductor.[4] Electric and magnetic fields increase with increasing voltage and current, respectively.[5] Although EMFs have separate electric and magnetic components, these components are linked and considered together as part of electromagnetic radiation energy. EMFs are part of a very broad range, or band, of electromagnetic radiation. This energy travels as a wave at a frequency, expressed as Hertz (Hz) or oscillations per second (s^{-1}). This paper focuses on EMF radiation (often referred to as radiofrequency radiation) of 60 Hz, the frequency of power in the U.S.[6]

There is concern that chronic exposure to even low anthropogenic frequency EMFs such as 60 Hz may cause cancer. Studies suggesting a correlation between childhood leukemia and high-current power lines began the environmental scare in the early 1980s. The reports attributed to starting the momentum of testing the EMF-cancer hypothesis included the Wertheimer & Leeper Denver study[7] and the Milham letter.[8] EMF research remains a highly debatable topic because of the enormous exposure, the remediation potential, the public's perception

4 *Id.;* Bette Hileman, *Health Effects of Electromagnetic Fields Remain Unresolved; Biological Effects from Low-level Nonionizing Fields Are Well Established but Clear Answers About Adverse Health Effects Continue to Elude Researchers,* Chemical & Engineering News, Nov. 8, 1993, at 15; U.S. National Inst. of Envtl. Health Sciences & Dep't of Energy, Questions and Answers About EMF Electric and Magnetic Fields Associated with the Use of Electric Power (1995) and William Hendee & John Boteler, *The Question of Health Effects From Exposure To Electromagnetic Fields*, 66 Health Physics 127 (1994).

5 C. Stephen Redhead & Christopher Dodge, Congressional Research Service Issue Brief, U.S. Congress, Health-Effects of Power-Line Electromagnetic Fields (EMFs) (October 7, 1993).

6 Joe A. Elder, Thermal, Cumulative, and Lifespan Effects and Cancer in Mammals Exposed to Radiofrequency Radiation (U.S. EPA 1994).

7 Nancy Wertheimer & Ed Leeper, *Electrical Wiring Configurations and Childhood Cancer,* 109 Am. J. Epidemiol. 273 (1979).

8 S. J. Milham, *Mortality From Leukemia in Workers Exposed to Electrical and Magnetic Fields,* 307 N. Engl. J. Med. 249 (1982).

of cancer risk, and inconclusive laboratory results. The Table above allows comparison of common appliances with typical EMF levels of 115kV and 230kV transmission lines. The field strength of a 230kV line at 200 feel is only a small fraction of that of an electric shaver at a foot, but data in the Table do not account for duration of exposure. To date, no causal relationship has been agreed to among the scientific community.[9] Yet, some scientists insist there is no conclusive evidence that "there isn't a problem," so they will continue their EMF studies.

Epidemiological Studies

Although numerous human epidemiological studies have been performed focusing on EMFs, the results have been far from decisive; some studies have found a correlation between EMF exposure and specific cancers such as leukemia and brain tumors, while others have found none.[10] Independent results from similar tests often support conclusions ranging between a positive correlation to no correlation.

Generally, epidemiologists express relative risk as a risk ratio to determine a "cause and effect" relationship. The risk ratio is the ratio of the disease incidence rate in the exposed population to that of the unexposed.[11] A relative risk ratio of 2.0 or more may be considered a strong, statistically significant association between exposure and disease, and supports a causal relationship. Some significant past EMF epidemiology risk ratio studies focusing on childhood leukemia and other cancers include the 1979 Wertheimer & Leeper, Denver study (child leukemia risk ratio of 2.35; all other cancers 2.22); the 1991 London et al., Los Angeles study (child leukemia risk ratio of 2.15); the 1993 Feychting & Ahlbom, Sweden study (child leukemia risk ratio of 3.80; all other cancers 1.30); and the 1993 Fajardo-Gutierrez, et al., Mexico study (child leukemia risk ratio of 2.63).[12] Several studies

9 *Supra* note 1; Suplee, *supra* note 2; *supra* note 4; Hawaiian Electric Industries, Inc., Electric & Magnetic Fields (visited July 1997) <http://www.hei.com/heco/emf.html> and Information Ventures, Inc., EMF-Link: A Biomedical Science and Engineering Clearinghouse on Electric and Magnetic Fields (EMF) (visited July 1997) <http://infoventures.com/emf/>.

10 Hawaiian Electric Industries, Inc., *supra* and Information Ventures, Inc., *supra.*

11 U.S. National Inst. of Envtl. Health Sciences & Dep't of Energy, *supra* note 3.

12 *Id.*; *supra* note 7; Stephanie London et al., *Exposure to Residential Electric and Magnetic Fields and Risk of Childhood Leukemia*, 134 Am. J. Epidemiol. 923

have been performed associating cancer (e.g., leukemia) and EMFs. Of these, the Denver and Swedish[13] studies are the most well known.

However, flaws can be found in both.[14] The Denver study's estimates of EMFs were determined by considering the size and number of power line wires, and the distance between residence and power lines. This determination lead to an indirect assessment of actual exposure to electromagnetic frequencies. When this study was repeated, actual readings were measured and no statistically significant relationship was found.[15] The Swedish study used risk ratios based on a limited number of cases, weakening its supporting argument of causality. It also estimated EMF levels that were assumed to be present at the time of cancer diagnosis. As with the Denver study, when EMFs were actually measured, no EMF-cancer relationship was found.

Many epidemiological studies have been performed which show no correlation between EMF exposure and cancer. One of the most widely studied groups is electrical utility workers. In a 1993 study of 36,000 workers at a large California utility company, no consistent evidence of an EMF-cancer association was found. A similar study involving more that 138,000 utility workers concluded that the results do not support an association between occupational EMF exposure and leukemia.[16] The recent NRC report examining more than 500 studies concerning EMFs and cancer also found no evidence.[17] Although the NRC report states that EMFs caused by power lines "[do] not constitute a threat to public health that would warrant an adjustment in national policy," the committee recommends continued research.[18] The committee noted some correlations, but it also found several contradictions that cloud

(1991); Maria Feychting and Anders Ahlbom, *Magnetic Fields and Cancer in Children Residing Near Swedish High Voltage Power Lines,* 138 Am. J. Epidemiol. 467 (1993) and A. Fajardo-Gutierrez et. al., *Close Residence to High Tension Electric Power Lines and Its Association with Leukemia in Children,* 50 Boletin Medico del Hospital Infantil de Mexico 32 (1993).

13 Feychting, *supra* note 12 and Maria Feychting and Anders Ahlbom, *Studies of Electromagnetic Fields and Cancer; How Inconsistent?* 27 Environ. Sci. Technol. 1018 (1993).

14 U.S. National Inst. of Envtl. Health Sciences & Dep't of Energy, *supra* note 3.

15 *Id.*

16 *Id.*

17 *Supra* note 1 and *supra* note 2.

18 *Supra* note 1.

epidemiological findings. Therefore, the NRC EMF committee believes that improved methodological studies should be performed.

Some suggestions to improve the methodology of future EMF studies include:

- Examining extraneous variables associated with living in areas with a large number of high EMF fields caused by power lines.
- Examining EMF exposures other than spot measurements, e.g., peak field strengths, field variability, time above a specific threshold strength, and frequency of transients above a given field strength.
- Studying children in areas of very high current configurations only.

The NAS Committee believes that the EMF-cancer connection warrants additional research, but until better-designed epidemiological studies are performed, a strong correlation between EMF exposure and cancer remains unproven. Although a correlation between EMF exposure and cancer seems to exist, it does not necessarily indicate a cause-and-effect relationship. Inferring such a relationship at this time would not be prudent due to inconsistent and mixed results, flawed testing methods, potential biases, and lack of solid evidence. If the suggestions regarding improvement of epidemiological studies mentioned above are incorporated into future studies, the answer to the EMF-cancer connection may be found.

Laboratory Studies

Several biological effects have been reported in studies of electric or magnetic fields. Overall, the effects attributed to EMFs have been small and difficult to reproduce. Very specific laboratory conditions are usually needed for the effects of EMFs to be detected. Some effects reported in laboratory studies are: altered functions of cells and tissues, decreased levels in the hormone melatonin, alterations in the immune system, accelerated tumor growth, changes in biosynthesis, and changes in human brain activity and heart rate.[19]

The first EMF cancer studies exposed laboratory animals to various types of EMFs for long periods of time. The exposed animals were examined for an increase in tumor incidence as compared to unexposed

19 U.S. National Inst. of Envtl. Health Sciences & Dep't of Energy, *supra* note 3.

control animals. The results obtained from these experiments were predominantly negative. There was a scattering of cancers among the animals, but no consistent pattern of tumors was found. The majority of scientists concluded that the tumors seen in the exposed test species were due to chance alone.[20]

Laboratory studies in the 1980's first reported that 60Hz electric fields greatly reduced pineal melatonin in rats. However, subsequent studies have failed to repeat these findings. A study of sheep found no effects of EMFs on melatonin levels of sheep raised beneath 500kV transmission lines. Two studies found that hamster melatonin production was also affected by EMFs. Subsequent studies designed specifically to replicate the earlier results found no such effect.[21]

EMF laboratory studies have yet to be consistent and conclusive on establishing a causal relationship. This also supports the findings of the NRC panel laboratory study review on EMF health hazards. Nonetheless, the NRC Committee has advised that more research be performed in the area of laboratory studies. The committee recommends the development of a standard method to produce and measure transient currents (more rapid changes in magnetic field strengths), with the purpose of testing the latest hypothesis of magnetic field/biological interactions. The Committee suggests that realistic models are needed to evaluate induced currents and fields at cellular and subcellular levels in the laboratory. It has also noted that more studies are needed to better understand wire codes, grounding, system currents, and contemporary versus historical exposure to support any laboratory associations.

Biological Plausibility

Another drawback in establishing a causal relationship between EMFs and cancer is the lack of a relationship between EMF exposure and a solid biological model (i.e., mode of action). A one-to-one relationship between exposure and a specific disease (e.g., leukemia) may indicate causality when it is biologically credible (e.g., radon exposure and specific lung cancers, smoking and lung cancers). However, without biological plausibility and confirmation of repeat

20 Information Ventures, Inc., *supra* note 9.

21 U.S. National Inst. of Envtl. Health Sciences & Dep't of Energy, *supra* note 3.

findings, such specificity can be the result of serious bias and confounding errors. Moreover, without clear biological understanding, EMF exposure and its implications to human health could not be truly understood. Some hypothesized EMF exposure biological models currently under scientific study are discussed below.

EMF Radiation -The Punch Unmasked

One of the most controversial aspects of anthropogenic EMF exposure and its relation to cancer is whether there is sufficient energy to damage cells. EMF radiation at this frequency is too low to engage the single-photon dissociation mechanism or even cause serious cellular danger from thermal heating. The energy of a single photon from EMF emissions can be estimated as follows:

A. The velocity of light in a vacuum is:

$c = \nu \bullet \lambda = 3.0 \times 10^8$ meters/second (m/s) (Equation 1)

Where:

c = velocity of light in a vacuum (3.0×10^8 m/s)

ν = frequency (cycles per second (s^{-1}) or Hz)

λ = wavelength (m).

B. The energy of a photon is related to wavelength and frequency, by Planck's constant and the velocity of light in Equation 1 (in a vacuum).

$E = h \bullet \nu = (h + c) / \lambda$ (Equation 2)

Where:

E = energy (Joules (J) per photon)

h = Planck's constant (6.62×10^{-34} J • second)

By substituting 60 Hz (the radiofrequency of electricity in the U.S.) and Planck's constant in Equation 2, and using Avogadro's number (6.02×10^{23} photons/mole), the energy of EMF radiation at this frequency is estimated to be 2.4×10^{-11} kJ/mole. This energy is orders of magnitude too small to cause the single photon dissociation mechanism (i.e., ionization) within molecular bonds of organic molecules (average bond energy of approximately 400 kJ/mol).[22] Obviously, the kinetic energy of EMFs alone does not support a plausible biological cause of cancer.

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22 H. M. Kingston, Duquesne University's Environmental Science Homepage (visited July 1997) <http://nexus.chemistry.duq.edu/snes/esm/Course_Material/ESM551/Index551.HTML>.

Other Hypotheses of Plausibility

Although EMFs lack the ionizing energy to cause biological effects, research is focusing on other hypotheses (none yet conclusive) to identify potential EMF-cancer relationships. Briefly, these hypotheses include:

The Transductive Hypothesis: The weak signals from EMFs are hypothesized to affect the movement of biological messages among cells. This hypothesis especially focuses on the flow of calcium which is used to "communicate" chemically and electronically on the cellular level. Researchers believe that by interfering with cellular communication mechanisms, EMFs can change actions of endocrines (i.e., hormones), neurotransmitters, the immune system, and cancer promoter molecules at cell surfaces.

The Melatonin Hypothesis: This hypothesis focuses on identifying the potential of EMFs to inhibit melatonin by acting on the pineal gland in the brain.[23] Melatonin inhibits many cancers (e.g., prostate, breast, skin) by affecting tumor growth enhancing endocrines. Since low melatonin is believed to be a risk factor in breast cancers, this hypothesis could potentially explain the occurrences of some male breast cancers found in electrical workers.[24]

The Receptor Molecule Change Hypothesis: EMFs are presumed to influence endocrines (i.e., hormones). This hypothesis is based on the premise that EMFs affect cell membranes by modifying the shape of cellular receptor molecules and, therefore, their function.[25]

The Magnetic Crystal Hypothesis: Since human brain contains magnetite crystals, some scientists hypothesize that under the influence of weak magnetic fields of EMFs, human cells may be affected, leading to cancer.[26]

The Free Radical Hypothesis: This hypothesis focuses on the premise that the magnetic component of EMFs slows the recombination of free radicals found in tissue. Free radicals are known

23 Hileman, *supra* note 3; The Electric Power Research Institute, EMF Research (1993) and William Bennett, *Cancer and Power Lines,* Physics Today, April 1994, at 23.

24 Alan Newman, *Field of Dreams? Electromagnetic Fields and the Links to Cancer,* 26 Environ. Sci. Technol. 1714 (1992).

25 Hileman, *supra* note 4.

26 *Id.*

cancer promoters. It is proposed that if this process occurs it would increase the probability, or likelihood, of the radical diffusing and reacting with other biomolecules, leading to the promotion of cancer.[27]

There are many theories for the potential association between EMFs and cancer, yet they remain as such. The recent NAS EMF committee's review of health effects of exposure to EMFs recognizes that the lack of a biological mechanism is a "serious barrier" to account for any genuine health effects, either good or bad.[28] The NAS does recognize however, that there appears to be genuine biological effects at higher magnetic field strengths. It also feels that well planned and executed mechanistic studies at higher strengths can lead to biological understanding of effects at lower magnetic field strengths. It stresses, nonetheless, that laboratory studies must focus on scientific control and adequate detail for replication. These are areas, it states, where other published studies fail.

The NAS EMF review committee does identify areas of mechanistic research that appear promising at this time. It believes that research in certain areas may help identify plausible biological mechanisms. These areas of continued research include: bone healing and therapeutic application, dose response relationship identification for in vitro signal transduction events and gene expression, biophysical mechanisms at high magnetic field strengths, potential co-carcinogenesis, and continued investigation of EMF exposed initiated animals.[29] All this notwithstanding, the current lack of a biologically plausible mechanism remains a question that must be identified to form to a solid causal relationship between low-level EMF exposure and an increased risk of cancer. Until these poorly understood mechanisms of action are identified, EMF exposure and its connection to cancer remains a controversial frontier science.

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27 *Id.*

28 *Supra* note 1.

29 *Id.*

Conclusions

Research at this time suggests that there is no confirming evidence linking low level EMF exposure to an increased risk of cancer; that is, exposure to low-level EMFs is not a carcinogenic health risk.[30] This conclusion is especially supported by inconsistent epidemiology studies and lack of a biological model. Those studies suggesting a correlation may be subject to serious doubt and errors, some of which may be overlooked. Moreover, the lack of a solid biological model that can satisfactorily explain the cancer promotion mechanism limits credibility to the EMF-cancer hypothesis. However, due to some disagreement in the scientific community on the NRC panel's findings, and until a model is identified which can be effectively tested and widely supported independently, the EMF issue will remain inconsistent, marginal, and open for debate.[31] Although there are significant uncertainties and inconclusive evidence with this and other hypotheses, the EMF-cancer promotion hypothesis remains legitimate and will lead to research for understanding previous associations between low-level EMF exposure and human health risks, if any.

30 *Id.*

31 *Supra* note 24.