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CHAPTER 10

Biological Effects of Low Frequency Electromagnetic Fields[1]

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10.1 INTRODUCTION

The biological effects of low frequency electric and magnetic fields[2] (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 abated the controversy associated with the harmful effects of electromagnetic fields. If anything it has polarized scientists into two camps, those who think exposure to low frequency electromagnetic fields causes health effects and those who do not. Those who believe there is a causal association are trying to find the mechanism responsible and those who question the concept of causality think this research is a waste of time and money.

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 confuse 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 three major reports, with multiple contributors with diverse expertise, have been published recently on the health effects of low frequency electric and magnetic fields: one by the U.S. National Research Council (1997), another by the National Institute of Environmental Health Sciences (Portier and Wolfe, 1998), and the most recent, still in draft form, by the California

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[1] Note: An expanded version of this paper can be found in Environmental Reviews **8**: 173-253 (2000). Research published since 2000 has been incorporated in the present paper.

[2] Magnetic field and magnetic flux density are used interchangeably in this document although the correct term is the later.

EMF Program (2001). These influential reports attempt to make sense of the many, and sometimes contradictory, documents from different fields of study, related to the health effects of power-line frequency fields.

The purpose of the present paper is three-fold:

(1) To characterize human exposure to low frequency electromagnetic fields;

(2) To identify key biological markers and possible mechanisms linked to EMF exposure;

(3) To comment on the concept of scientific consistency and bias.

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 dependence on electric power, computer technology, and wireless communication, and it is likely to be of interest to a large population using, manufacturing, selling, and regulating this technology.

10.2 BACKGROUND INFORMATION

In the broadest sense, electromagnetic research involves three major sources of electromagnetic energy: those generated by the earth, sun and the rest of the cosmos (geofields); those generated by living organisms (biofields); and those generated by technology (technofields).

These fields interact and it is these interactions that most interest us. Solar flares sufficiently powerful to knock out satellites or to disrupt power distribution and the reflection of radio signals by the ionosphere are examples of geofield and technofield interactions. Photosynthesis, tanning, weather sensitivity are examples of geofield and biofield interactions.

The areas of current scientific debate are the interactions between living organisms (biofields) and technologically generated fields (technofields) at power line frequencies (60 Hz in North America and 50 Hz elsewhere) and at frequencies generated by computers and cell phones in the kilo (10^3), Mega (10^6) and Giga (10^9) Hertz range.

Until recently, frequencies below the microwave band were assumed to be "biologically safe". This began to change in the 1960s and early 1970s. Several months after the first 500 kV substations became operable in the Soviet Union high voltage switchyard workers began to complain of general ill health (Korobkova *et al.* 1971). The electric field, with maximum intensities between 15 and 25 kV/m, 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. Biological effects were reported above 5 kV/m. The harmful effects of high voltage power lines on substation workers and their families have since been document elsewhere (Nordstrom *et al.* 1983, Nordenson *et al.* 1994).

Nancy Wertheimer and Ed Leeper were the first to report the potential harmful effects of power lines associated with residential rather than occupational exposure. An increased incidence of childhood leukemia, lymphoma, and nervous system tumors was associated with residential exposure to power line-frequency fields in Denver Colorado (Wertheimer and Leeper 1979). Paul Brodeur did much to publicized this type of information in *The New York Times* and elsewhere (Brodeur 1993), alerting the public and enraging members of the scientific community who were unwilling to accept the Wertheimer and Leeper results.

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 others confirmed the Wertheimer and Leeper results.

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, leukemia, and breast cancer. Similarities between childhood and adult cancers raised concern.

One problem with the early epidemiological studies was that information on exposure was scarce. Wire codes provided a surrogate metric for the magnetic field. In residential settings the magnetic field, which penetrates through walls, was assumed to be more important biologically than the electric field, which does not. Once portable gauss meters sensitive to power line frequencies became available, the spot measurement and 24-hour 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 Ahlbom 1993, Savitz et al 1988), although a reassessment of earlier studies points to a stronger association between wire codes and magnetic field measurements (Savitz and Poole 2001).

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. Whether magnetic flux density is the only biologically important metric, or, indeed, the one we should be measuring remains to be determined.

Epidemiological studies were complemented by *in vivo* and *in vitro* studies attempting to explore the mechanisms underlying the EMF effect. Because of the novelty of this type of research there were (and still are) no standardized protocols for testing. Experimental intensities for magnetic flux density range from less than 0.1 □□ to greater than 300,000 □□ (300 mT); daily exposure varies from 30 minutes to 24 hours; and duration of exposure extends from days to years. Some of the tests involve continuous, homogeneous fields, others involved gradients, and still others used intermittent fields with on:off cycles ranging from seconds to hours. Interpreting such a wide array of exposure conditions is not an easy task and thus conflicting conclusions are to be expected depending on the scientific weight placed on individual studies.

10.3 EXPOSURE

10.3.1 Residential Exposure

In a residential setting there are three major sources of technologically generated magnetic fields: appliances, the indoor distribution system consisting of indoor wiring and grounding, and the outdoor distribution system consisting of either below or above ground wires and transformers. The early studies assumed that power lines provided the major source of magnetic field inside the home and both indoor wiring and appliances were ignored, although some studies attempted to minimize indoor sources by turning appliances and lights off. More recent studies recognize the importance of these additional sources and enable us to calculate cumulative and time-weighted average (TWA) magnetic flux densities for a given environment.

10.3.1.1 Outdoor Distribution System

Wire codes, used to estimate exposure to magnetic fields (based on distance and wire configuration) may provide a good relative surrogate for the magnetic flux density within a community; however, they become less reliable when different communities are compared. The magnetic flux density associated with outdoor wiring in a residential setting can range from less than 0.03 to greater than 8 μT, although the values are generally below 1 μT for most homes (Havas 2000, Table 7).

The electric field was not considered to be important in the residential epidemiological studies because they cannot penetrate building material. Electric fields immediately beneath overhead neighborhood distribution lines are likely to be less than 30 V/m (Havas 2002, in press). However, there is a trend among electric utilities to increase the voltage of power distribution lines to minimize resistance and thus energy loss. As voltage increases so does the intensity of the electric field, and studies report that the harmful effects associated with magnetic field exposure may be worse in the presence of a strong electric field (Miller *et al.* 1996, see paper by Henshaw in these proceedings on particulate density near power lines).

10.3.1.2 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 (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).

EPRI (1993, as cited in NIEHS 1998) conducted a survey of 1000 homes and took both 24-h and spot measurements in different rooms. The median magnetic flux densities for 24-h measurements vary more than 10 fold with 50% of the homes exceeding 0.05 □□ (and 1% of the homes exceeding 0.55 □□). The highest wire code category (VH, very high current configuration) in the Wertheimer and Leeper (1982) study was 0.25 □□ and according to the EPRI study, 5% of the homes exceeded this value.

The spot measurements for magnetic flux density in the EPRI (1993) study differed in rooms and some were sufficiently high to suggest faulty wiring. Rooms with the highest average spot measurements ranged from 0.11 □□ (50th percentile, 50% of homes exceeded this value) to 1.22 □□ (99th percentile, 1% of homes exceeded this value).

Improperly installed indoor wiring can account for very high fields. In a survey of 150 buildings, Riley (1995) reported that the majority (66%) of the high fields above 3 mG (0.3 □□) 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 feet. The greater the separation the higher the magnetic field that is produced and the less it decreases with distance ($1*r^{-1}$ for a single line conductor rather than $1*r^{-2}$ for close parallel line conductors). Changes from knob-and-tube to twisted cables have reduced magnetic fields in modern homes.

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). Rerouting or adding ground return wires can produce background magnetic fields in the order of 1 □□ in the home (Bennett 1994), a value that exceeds exposure in many occupations.

10.3.1.3 Appliances

EPA (1992) measured the magnetic fields produced by a variety of household and office appliances. According to this study, the magnetic fields generated by appliances differ enormously and drop off rapidly (generally $1*r^{-3}$) with distance. Magnetic flux densities, range from 150 □□ for can openers to less than 0.1 □□ for tape players. There are considerable model differences as well. For example, hair dryers can range from 70 □□ to 0.1 □□ 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. Among household appliances electric can openers generate some of the highest fields recorded (50 to 150 μT at 15 cm).

10.3.1.4 Components of Residential Exposure

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

10.3.2 OCCUPATIONAL EXPOSURE

Just as the early residential epidemiological studies used wire codes as surrogates for magnetic fields, the occupational studies initially based their result on job titles. As interest in occupational exposure increased, more measurements of magnetic fields in various occupational settings 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 are 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.

Portier and Wolfe (1998) summarized a vast amount of data for time-weighted-average (TWA) magnetic field exposures according to industry type. The original data were ranked and classified into percentile groupings. The 95th percentile was at 0.66 μT and can be considered very high exposure 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.

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 (mean 3 uT, Havas 2000). 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 (mean 1.4 to 3.6 μT). In transportation, railway workers have high exposures (mean 4 μT). Among metal workers, welders and those who do electrogalvanizing or aluminum refining tend to have high magnetic field exposure (mean 2 μT).

Another industry with notable exposure is telecommunications, especially telephone linemen, technicians, and engineers (mean 0.35 to 0.43 μT). Individuals repairing electrical and electronic equipment (0.16 to 0.25 μT) can also be exposed to above average magnetic fields, as can dental hygienists (mean 0.64 μT) and motion picture projectionists (mean 0.8 μT). Those involved in forestry and logging have a high average exposure of 2.48 μT (Havas 2000).

In an office environment, magnetic fields are generally at or below the 50th percentile (≤0.17 μT) except near computers, photocopiers, or other electronic equipment. People in sales, in computer services and in the construction industry are generally exposed to lower magnetic fields. Teachers have below average exposure with a TWA magnetic flux density of 0.15 uT.

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 airplane pilots, streetcar and trains conductors, hairdressers (hand-held hairdryers), carpenters (power tools), tailors and seamstresses (sewing machine), metal workers, loggers, and medical technicians.

10.3.3 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 are much higher than for most occupational exposure. According to Bennett (1994), magnetic flux densities of 24 μT have been recorded 1 meter above the floor and 4 meters 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 uT.

Passengers may not be on these commuter trains for long but workers are exposed to them all day. The MAGLEV (magnetic levitation) electric train generates 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 as the ac frequency is increased. Magnetic flux densities of 50,000 μT (50 mT) in the passenger compartment where people work have been reported (Bennett 1994).

Airplanes generate a 400 Hz electromagnetic field. The highest fields are in the cockpit with values greater than 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 and 0.3 μT are more common (Havas, unpublished data). Since flights generally last several hours, cumulative exposure can be considerable. 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 (Havas, unpublished data). Drivers are exposed to higher magnetic fields in luxury vehicles with electronic equipment and in smaller than larger vehicles, presumably due to proximity to the alternator. The fan, air conditioning, heating, as well as the driving style (acceleration) 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 (Havas, unpublished data).

10.3.4 COMPLICATIONS WITH EXPOSURE

Although we are beginning to get a sense 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 field. Although the previous section and much of the literature have focused primarily 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). Also, external magnetic fields can generate internal electric fields, so a distinction between the two is not simple. The biological response is likely to be a function of the fields within our bodies rather than the external fields to which we are exposed and this 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 is 50/60 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. Some of the studies suggest that biological effects 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 produce the same biological response. A good model for biological response may be one based on the radio tuned to a specific modulation (Frey 1994).

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 this area of research, concerned with EMF exposure is complex and of utmost importance if we are to understand biological interactions with electromagnetic fields.

10.4 BIOLOGICAL RESPONSE TO EMFS

10.4.1 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 leukemia, nervous system tumors and, to a lesser extent, lymphoma among children; and leukemia, nervous system tumors, and breast cancer among adults.

10.4.1.1 Cancer in Children

Irrespective of which metric is used (wire codes, distance, measurements, or calculations of exposure), when viewed as a whole, many of the studies on childhood leukemia suggest an odds ratio (OR) above 1. Critical distances appear to be approximately 50 m from a power line and critical magnetic flux densities are above 0.2 uT. Daytime spot measurements give the lowest ORs while median nighttime measurements give the highest.

Several studies suggest a dose/response relationship. Feychting *et al.* (1993, 1995) reported a significant OR of 2.7 above 0.2 □□ and 3.8 above 0.3 uT. Schuz *et al.* (2001) reported a non-significant 1.33 OR between 0.1 and 0.2 uT, a significant 2.4 OR between 0.2 and 0.4 □□and 4.28 OR above 0.4 uT, based on nighttime exposure. These values are low compared with other known carcinogens like cigarettes and asbestos but are certainly well above background.

Two recent meta-analyses of childhood cancer conclude that exposure to magnetic flux densities in excess of 0.4 □□are associated with an increase risk of childhood leukemia. The first of these meta-analyses (Ahlbom *et al.* 2000) includes data from 9 countries and is based on 3,203 cases and 10,338 controls. Above 0.4 □□ the relative risk is 2.0, with a range of 1.27 to 3.13, which is statistically significant (P=0.002). This means there is a 2-fold increased risk for children developing leukemia. Fortunately, a very small percentage (0.8%) of the children in this study were exposed to fields above 0.4 uT.

In the second meta-analysis based on 19 studies Wartenberg (2001) concludes that with widespread exposure to magnetic fields there may be a 15 to 25% increase in the rate of childhood leukemia, which is "a large and important public health impact." In the United States as many as 175 to 240 cases of childhood leukemia may be due to EMF exposure.

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).

10.4.1.2 Cancer in Adults

For adults, the link between EMF exposure and leukemia, brain tumors, and breast cancer, 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 although it is very difficult to accurately estimate dose in an occupational setting. For this reason it is difficult to provide a threshold value, if indeed one exists, based on the information available. Studies suggest that cumulative exposure is important (Miller *et al.* 1996)

Among the cancers, the one with the highest odds ratio is breast cancer in men. Several studies indicate a relative risk above 4 for men (Demers *et al.* 1991, Tynes *et al.* 1992, Floderus *et al.* 1994), while the highest value for women is 2.17 (Loomis *et al.* 1994). 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 5000 women in Canada and as many as 44,000 in the United States die from breast cancer each year (WHO 1998).

Laboratory studies report an increase growth rate for estrogen-responsive breast cancer cells above 12 mG (1.2 □□) (Liburdy *et al.* 1993). These studies have been independently replicated by at least two other labs and show a causal relationship between magnetic fields and breast cancer growth.

Astrocytoma is the most common type of brain cancer associated with EMF exposure (Floederus *et al.* 1993, Theriault *et al.* 1994, Lin *et al.* 1985). Floederus *et al.* (1993) reported a dose-response relationship for astrocytoma with a non-significant increased OR of 1.3 below 0.19 uT; a statistically significant OR of 1.7 between 0.2 and 0.28 □□ and a significant OR of 5.0 above 0.29 uT.

10.4.2 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, 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).

10.4.2.1 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 □□at a distance of 5 cm, and ceiling cable heating produces ambient magnetic fields of approximately 10 □□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 □□ 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 effect was between 0.2 and 2 uT, well within the range of the Wertheimer and Leeper (1986, 1989) studies. Melatonin has many functions one of which is the regulation of sex hormones, estrogen and progesterone, which are critical for full term pregnancies.

Li *et al.* (2002) reported an increased risk of miscarriage for women exposed for any length of time during a normal 24-hour period to a magnetic field above 16 mG (1.6 □□). The California EMF Program draft report (2001) calculates that as many as 40% of the miscarriages (24,000 miscarriages) each year in California may be attributed to magnetic field exposure.

10.4.2.2 Maternal VDT 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). 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-VDT 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 hr 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). 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).

10.4.2.3 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, Feychting *et al.* 2000).

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. 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 experienced some difficulty conceiving when the husband worked in a high-voltage switch yard (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 *et al.* 1977; Free *et al.* 1981).

Feychting *et al.* (2000) reported a statistically significant association between paternal exposure to magnetic fields at or above 0.3 □□with a two-fold increase in childhood leukemia but no risk with childhood brain tumors.

Wilkins and Koutras (1988) conducted a case-control study of Ohio-born children who had died of brain cancer during 1959 and 1978. Case fathers were more likely than control-fathers to be electrical assemblers, installers, and repairers (OR=2.7, 95% CI=1.2-6.1); welders and cutters (OR=2.7, 95% CI=0.9-8.1); or farmers (OR=2.0, 95% CI=1.0-4.1). Although chemicals cannot be ruled out as potential confounders, these industries (except perhaps farming) tend to have higher than average EMF exposure. A paternal occupational study that can differentiate between EMF and chemical exposure and the risk of childhood cancers is needed.

10.4.3 DEPRESSION

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

Epidemiological Studies-Depression scale. A higher percentage of depressive symptoms were recorded among people living near the line compared with the control population. The odds ratio was 2.1 (1.3-3.4, 95% confidence interval). 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 Breck-Friis *et al.* 1985, 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 and that nighttime exposure may be more biologically critical than daytime exposure.

10.4.4 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 3 independent clinical series of non-familial Alzheimer's disease in Finland (2 series) and California, USA (1 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, 1.7-8.9 95% CI) were observed for the combined data sets for females working primarily as seamstresses and dress makers. The OR for males was also above 1 (OR 1.9) but was not statistically significant.

Sewing machines generate very high magnetic fields, 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 broader population.

10.4.5 AMYOTROPHIC LATERAL SCLEROSIS (ALS)

Several studies link EMF exposure to amyotrophic lateral sclerosis (ALS). Three studies have reported a statistically significant increase in ALS, with a relative risk from 1.3 to 3.8, for electric utility workers (Deapen and Hendersen 1986, Savitz *et al.* 1998a,b, Johansen and Olsen 1998). The California EMF Program classifies EMFs as possibly causal agents in ALS. Both Alzheimer's disease and ALS are neurodegenerative diseases.

10.4.6 ELECTROMAGNETIC SENSITIVITY

One of the most detailed and carefully controlled experiments to determine the existence of electromagnetic field sensitivity was conducted by Rea and co-workers (1991). A four-phased approach was used 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 (25 patients) and comparing them with controls; and finally retesting the most reactive patients (16 patients) 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 subjects 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.

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 frequencies.

People who claim to be electrically sensitive can't use computers and develop headaches and "brain fog", which they describe as an inability to think clearly, when they are exposed to fluorescent lighting for any length of time. The symptoms can be quite debilitating but often the medical profession's response is that the symptoms are probably psychosomatic. Hence the diagnosis creates more stress for the patient and does not correct the underlying cause of the problem.

10.4.7 THE ELUSIVE MECHANISM

The effect of an environmental pollutant, such as DDT, lead, 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.

10.4.7.1 Melatonin Production

Melatonin is a neurohormone that regulates sleep cycles, sex hormones, and reproduction. It is produced by the pineal gland, a light-sensitive pea-shaped gland located in the middle of the brain. In animals the pineal gland serves as a compass (it detects changes in the geomagnetic field), a clock (it sense changes in visible light, a part of the EMF spectrum, and induces sleep), and a calendar (it senses changes in photoperiod and induces hibernation as well as ovulation and thus controls reproductive cycles in seasonal breeding animals).

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 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 senses changes in electromagnetic frequencies other than those associated with visible light including static and power frequencies fields (Liburdy *et al.* 1993). 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-responsive which means their growth is promoted by estrogen. Post-menopausal women have an increased risk of developing breast cancer if they take estrogen supplements. High levels of melatonin (which suppress 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.

Women sleeping under electric blankets have lower night-time melatonin levels (Wilson *et al.* 1990), which 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 a natural anti-cancer chemical (Reiter and Robinson 1995). 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.

10.4.7.2 Mitosis and DNA Synthesis and Chromosomal Aberrations

The dynamics 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 and 4 kHz and intensities from 2.3 to 560 □□ and measured the incorporation of tritiated thymidine. DNA synthesis was enhanced during the 24-hour incubation. The threshold for this effect is estimated to be between 5 and 25 uT/sec (product of magnetic flux density (rms) and frequency) and is within the range associated with abnormal chick embryo development (10 uT/sec).

10.4.7.3 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 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. 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 were important for biological effects (Adey 1980, Blackman 1985). Calcium is critical for many cell processes and changes in its flux could have significant and diverse effects on biota.

10.5 COMMENTS ON BIAS AND CONSISTENCY

10.5.1 Executive Summary of Three Major Reviews

Since 1997, three major reports have reviewed the literature on the biological effects of low frequency electromagnetic fields. Of interest is the shift in conclusions of these three reports during a 5-year period.

10.5.1.1 US National Research Council Expert Committee (1997)

The overall conclusions of the NRC Expert Committee, as stated in the Executive Summary, are as follows (NRC 1997, page 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."

"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."

10.5.1.2 National Institute of Environmental Health Science Executive Summary (1998)

The evaluation of the majority of the Working Group is that extremely low frequency (ELF) EMF can be classified as "*possibly carcinogeni*c" 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*." (Portier and Wolfe 1998, page 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*." (Portier and Wolfe 1998, page 400).

10.5.1.3 California EMF Program, Executive Summary (Draft 3, 2001)

The California Department of Health Services initiated the California EMF Program on behalf of the California Public Utilities Commission. Three reviewers examined epidemiological studies linking EMFs to 13 health conditions to determine whether these links might be causal in nature. These assessments were based on previously developed Risk Evaluation Guidelines and criteria developed by the International Agency of Research on Cancer (IARC).

Based on IARC Guidelines, the reviewers state that electromagnetic fields are:

- *Possible Human Carcinogens to Human Carcinogen:* based on childhood and adult leukemia
- *Possibly Causal*: based on adult brain cancer, miscarriage, and Lou Gehrig's disease, and that there is
- *Inadequate evidence* for male breast cancer, female breast cancer, childhood brain cancer, suicide, Alzheimer's disease, acute myocardial infarction, general cancer risk, birth defects, low birth weight or neonatal deaths, depression and electrical sensitivity.

The reviewers calculate that 1150 deaths per year with an additional 24,000 miscarriages annually may be attributed to EMFs. These estimates are much higher than the sum of annual non-fatal cancers associated with chloroform in chlorinated drinking water (49 cases), benzene in ambient air (100 cases); formaldehyde in indoor air (124 cases); or naturally occurring indoor radon (570 cases), all of which are currently regulated environmental agents. Over 1000 deaths with a much larger number of non-fatal cancers in California is a serious environmental hazard that requires serious regulatory attention.

During a relatively short period of 5 years we have moved from "no evidence links contemporary measurements of magnetic-field levels to childhood leukemia" (NRC 1997); to electromagnetic fields being classified as a *possible carcinoge*n based on childhood and adult leukemia (Portier and Wolfe 1998); to electromagnetic fields classified as *possibly causal* for 5 health conditions, those identified by NIEHS as well as adult brain cancer, miscarriage, and Lou Gehrig's disease (California EMF Program 2001). If this trend continues, with better designed studies, more of the health conditions listed above are likely to be linked in a causal way with electromagnetic field exposure. The increasing connection between EMF exposure and estrogen-responsive breast cancer among younger woman rather than all forms of breast cancer among women of all ages is one case in point.

10.5.2 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 sees the noise while the other sees the signal. Differentiating between prejudicial and cultural bias is difficult.

Two strong cultural biases are presented in the literature: One represented the views of epidemiologists and the other that of physiologists. These conflicting perspectives are both well presented in the NIEHS and California reviews.

The NRC (1997) document is culturally biased towards the physical sciences and is highly critical of positive associations between EMF exposure and effects to the point that it raises questions of prejudicial bias. Scientific studies that suggested detectable biological responses to electromagnetic fields in the section on cellular and molecular effects and in the section on animal and tissue effects were down played so frequently that I began to think, "Methinks, thou doth protest too much!" For a detailed assessment of this refer to Havas (2000). Positive studies (those finding an association between exposure and effects) were criticized, while negative studies (those finding no association) were accepted at face value.

Another example of bias is the absence of studies dealing with occupational exposure in the executive summary despite the fact that they were included in the body of the text. 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.

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). (pg. 179).

. . . 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. 1994). Brain cancer showed much more modest increases (relative risk of 1.5-2.8) with increased magnetic field exposure. (pg. 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) . . . (pg. 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 . . . (pg 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 (pg 181). Yet this is exactly what the NRC report did, it ignored some vital pieces of information in its executive summary.

10.5.3 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 understanding the importance atmospheric pressure

we may claim that two studies, each of which report a different temperature for the boiling point of water, are inconsistent. It's 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 bone growth. 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 vitro* studies show), then the tumor 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 tumor would be agent (or initiator) specific. Furthermore, an underlying mechanism that supports tumor promotion (of several types of tumors) is the melatonin hypothesis.

10.5.4 CLASSICAL CHEMICAL TOXICOLOGY AND EMF EXPOSURE

Some of the apparently contradictory results may be due to the fact that 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, page 4). This makes sense once we recognize that living organisms generate and use low frequency electromagnetic fields in everything from regeneration through cellular communication to nervous system function. Frey goes on to suggest that high frequency EM waves may carry low frequency EM signals to the cell.

10.6 CONCLUSIONS

After a decade 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 vary with individual sensitivities, 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. The scientific work is unfinished 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 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.

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