

CHRONIC ELECTROMAGNETIC STRESSORS IN THE ENVIRONMENT:
A RISK FACTOR IN HUMAN CANCER

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I. INTRODUCTION

Electromagnetic fields are real, physical, incorporeal entities that arise from the existence and motions of atomic charges. Electromagnetic waves are electromagnetic fields that propagate through space and, after generation by the source, are physically unconnected to it. Typical examples are radar, microwave ovens, and radio and television signals. The second class of electromagnetic fields consists of electric and magnetic fields. They are distinct but frequently superimposed fields that arise in the vicinity of wires carrying electric currents. Although these fields are stationary in the sense that they do not propagate through space, their magnitude or direction may be time-dependent. The strength

of electric and magnetic fields decreases (usually in a complicated fashion) with increasing distance from the source. Typical sources are high-voltage powerlines, electric blankets, and airport metal-detectors.

Electromagnetic fields became increasingly common constituents of the general and workplace environments early in the 20th century, but some lifestyles and occupations are associated with more than the average amount of exposure to electromagnetic fields. People who live near high-voltage powerlines, for example, are chronically exposed to electric and magnetic fields that are significantly stronger than those usually experienced by the general population. People who use electric blankets similarly experience stronger fields for longer durations compared to the general population. Navy shipboard personnel are exposed to electromagnetic fields from many shipboard radars, and in this regard their work environment differs significantly from that of other young men. People living near airports are exposed to radar beams used to locate and guide airplanes. Such residential areas differ from other socio-economically comparable neighborhoods with regard to the constituency of the electromagnetic background. Amateur radio operators experience more electromagnetic-field exposure than the general population because of their proximity to radiating antennas. Many other patterns of exposure in the general and workplace environments can be identified with increased intensity and duration of exposure to electromagnetic fields. The existence of sub-groups in the general population that experience increased exposure raises the question of whether the exposed groups have an increased incidence of certain diseases that may be linked to this exposure.

Despite the accelerating presence of electromagnetic fields in the general and workplace environments, their possible public-health significance was

largely unstudied in the United States until the late 1970s. But the situation changed, due largely to developments in two partially-related areas. A better understanding of the physiological role of the body's innate electrical activity has been achieved, and has led to clinical applications of a variety of electromagnetic devices intended to aid in the diagnosis and treatment of disease. The energy imparted to the body by the therapeutic devices is frequently less than that derived from some typical environmental and workplace conditions, and the possible consequences of environmental and workplace exposure could not be ignored. The second development was the generation of a large body of research data on animals that revealed previously unsuspected effects of electromagnetic fields on biological systems. In 1979, epidemiologists began reporting on direct studies of possible correlations between environmental exposure and disease. The bulk of such studies focused on one class of disease — cancer.

These studies have some potential methodological shortcomings — whether they actually exist is a different question — as well as unique difficulties that deserve attention. Many factors besides electromagnetic fields are associated with particular living or working conditions. People living near powerlines may be exposed to ozone from the corona discharge that occurs along the wires. Sailors aboard ship breathe in salt air and live in cramped quarters. People near airports are exposed to high noise levels. Amateur radio operators may breathe in solder fumes. The list of possible confounding factors is long. Bias in the choice of a control group is another obvious possibility tending to undercut the reliability of an apparent correlation between exposure and disease. One unique problem with electromagnetic-field studies is that the fields leave no physical trace of having been present in tissue. Unlike lead, asbestos, or cotton dust, there is no radiological, histopathological, or biochemical test for the actual presence of

electromagnetic fields in exposed individuals. A physiological dosimeter that records past exposure to electromagnetic fields does not exist.

Against the background of possible perturbing influences and uncertainties, a threshold question arises: do the present epidemiological studies provide sufficiently strong evidence to support the conclusion that environmental electromagnetic fields are a risk factor for cancer? In the next section we briefly describe all of the epidemiological studies which we could find that bear on this question. We also give our reasons for concluding that the question should be answered affirmatively.

The epidemiological studies are not conclusive regarding many important details. Cancer is a complex disease, and the physical nature of the interaction between electromagnetic fields and tissue is also complex. Even so, we believe that the evidence permits one to do more than merely link environmental electromagnetic fields with cancer: it permits the laying of a general framework for the mechanism by which the fields act on the body to produce disease. We address these points in the succeeding sections.

II. EPIDEMIOLOGY

Epidemiological Studies

One of the first recorded observations of a possible association between electromagnetic fields and cancer was made by Zaret, who found several small clusters of cancer among occupationally—exposed men (1). These included 2 cases of astrocytoma (brain tumors) among 18 workers servicing microwave communications equipment, 5 cases of cancer among a group of 17 men who

worked on a weapons system involving electromagnetic pulses, and 3 cases of cancer among 8 men employed as repairmen for airborne navigation systems.

During a study of occupational mortality in the state of Washington that involved 438,000 deaths during 1950–1979 (2), Milham found what appeared to be a disproportionately large number of deaths from leukemia among aluminum workers (20 deaths as opposed to the expected mortality of 10.6). Ordinarily, the excess deaths would have been attributed to chemicals present in the workplace environment, but similar chemicals were present in other workplace environments and these workers did not show excess leukemia deaths. Since strong electromagnetic fields are created as part of the aluminum—manufacturing process, he focused on job classifications that presumably involved occupational exposure to electromagnetic fields. Of the 11 occupations considered, Milham found more observed than expected instances of leukemia in 10 occupations including electricians, aluminum workers, linemen, power-station workers, and electrical engineers. Milham's overall data for both leukemia and acute leukemia is shown in Table 1.

Wright et al., used Milham's occupational designations and studied the possible link to leukemia incidence (1972-1979) for white males in Los Angeles County (3). There were no cases in 2 categories, but the number of observed cases exceeded the number of expected cases in 7 of the remaining 9 categories. One of the two occupations that did not show an increase in leukemia (welders and flame—cutters) was the same occupation that did not show an increase in the Milham study. The increase in incidence of all leukemia was not statistically significant, but the increase in both acute leukemia and acute myelogenous leukemia was significant ($P < 0.05$) (Table 1).

TABLE I

Leukemia Incidence (Mortality) in Men Occupationally Exposed to Electromagnetic Fields

<u>INVESTIGATOR</u>	<u>STUDY AREA</u>	<u>LEUKEMIA</u>		<u>ACUTE LEUKEMIA</u>	
		<u>Observed</u>	<u>Expected</u>	<u>Observed</u>	<u>Expected</u>
Milham	Washington	(136)*	(92)	(60)*	(36.7)
Wright	Los Angeles	35	27.2	23**	13.3
Coleman	England	113**	96.5	45	35

*P<0.01
**P<0.05

Coleman et al., examined the incidence of leukemia among men who were occupationally exposed to electromagnetic fields in southeast England (4). The 10 electrical occupations studied were essentially equivalent to the 11 categories used to classify American workers. They found a 17% excess of leukemias in the electrically-exposed occupations (Table 1). For 8 of the 10 occupations examined, more leukemias were observed than expected.

McDovall reported on a case-control study involving 537 deaths in England and Wales (males greater than 15 years of age) that died from acute myeloid leukemia in 1973 (5). The control group included all causes of death except leukemia. They found a consistently increased relative risk for the occupations that involved exposure to electromagnetic fields: occupationally-exposed men had a relative risk of acute myeloid leukemia of 2.3 ($P < 0.05$). In a similar case-control study Pearce et al., also reported that electrical workers in New Zealand were at increased risk of leukemia (6).

Milham studied the leukemia deaths that occurred in male members of the American Radio Relay League, a group of amateur radio operators (7). In 1971–83, 1,691 deaths among League members occurred in Washington and California. Twenty-four deaths from leukemia were observed, compared to the expected 12.6 ($P < 0.01$). Two deaths were observed (0.76 expected) in men who worked in occupations that involved electromagnetic exposure, and 3 deaths were observed (1.4 expected) in those who worked in all other occupations. The association between employment in occupations involving exposure to electromagnetic fields and membership in the American Radio Relay League therefore probably did not explain the leukemia excess.

Robinette et al., studied the effects of exposure to electromagnetic fields among Navy servicemen who graduated from training schools and served aboard ships during 1950–1954 (8). One group (20,781 men) consisted of subjects who worked as radiomen, radarmen, and aviation–electricians’ mates, and the second group (19,649 men) consisted of aviation, electronics, or fire–control technicians. The men in both groups were heavily exposed, both occupationally (1000 pW/cm^2) and after work hours (because the ship’s radars operated more than 8 hours per day), compared to typical exposure levels experienced by the general public in the United States in 1950–1954. The chief difference between the groups was the possibility that some men in the smaller group were occasionally exposed to $100,000 \text{ pW/cm}^2$. No differences in a variety of mortality and morbidity indices were found by the investigators that could be attributed to the difference in exposure. Fourteen deaths from leukemia were recorded among the high–exposure group, compared to 8 recorded from the low-exposure group. There were 16 deaths in the combined groups from eye, brain, and other nervous–system neoplasms. This represented 7.9% of all malignant deaths (16 of 202) as compared with the rate of 3.8% for the general population ($P < 0.01$) (9).

Lin et al., studied the relationship between occupation and brain-tumor mortality that occurred among white male Maryland residents between 1969–1982 (9). A total of 951 cases were included, consisting of 370 gliomas, 149 astrocytomas, and 432 brain tumors of unspecified type. Preliminary analysis showed more deaths among occupationally-exposed workers (electricians, electrical engineers, linemen) than expected (from 1970 Maryland Census data): 50 deaths from glioma and astrocytoma were observed (18 expected), 28 deaths from brain tumors of unspecified type (14.7 expected), and both differences were significant ($P < 0.01$). But a possible bias was introduced because the comparison involved mortality data from a 14-year span and occupation prevalence based on only one year. To overcome the problem, a case-control study was performed in which the control group consisted of white sales who died from causes other than malignant neoplasms, matched on age and date of death. It was found that patients in occupations involving exposure to electromagnetic fields exhibited more gliomas and astrocytomas than the controls: electricians (13 vs. 10), engineers (18 vs. 6) and utility company employees (19 vs. 11). No significant differences between the case and control subjects were seen with regard to brain tumors of an unspecified type. The patients who died from gliomas or astrocytomas were younger by an average of 5.1 years compared to the controls.

Between 1964–1978 there were a total of 157 cases of neuroblastoma in children under 15 years of age in Texas for which adequate records could be obtained (10). A control group was formed from randomly selected birth certificates, and data on parental occupation was abstracted and analyzed based on a system in which occupational exposures were classified according to presumed chemical exposures. Cluster 7 (formed on the basis of presumed moderate exposure to hydrocarbons) was associated with an increased risk of neuro-

blastoma (odds ratio 3.17, $P < 0.05$). Cluster 7 included occupations that both involved (electricians) and did not involve (printers) exposure to electromagnetic fields. When the data was reanalyzed to include only Group 1 occupations (electricians, electric and electronic workers, linemen, welders, and utility employees) the odds ratio for neuroblastoma was 2.14. When Group 1 was expanded to include parents who sold or serviced electrical equipment, the odds ratio was 2.13 ($P = 0.05$). When only electronics workers were evaluated, the odds ratio was 11.75 ($P < 0.05$).

The authors did not specify explicitly whether it was the occupations of the fathers or mothers that were being evaluated (other than to state that few of the mothers were employed outside the home at the time of birth of their children). If the link with neuroblastoma actually involved electromagnetic fields, it may have resulted from prenatal exposure of the mother. Other studies have reported associations between nervous—system tumors in children whose fathers worked in occupations in which they were exposed to various solvents, and such a link may be responsible for the observed association with neuroblastoma. Perhaps the most intriguing explanation for the observed association is the possibility that it was linked to electromagnetic—field exposure of the children's fathers. There is some confirmatory support for this possibility: retinoblastoma occurred more often among children whose fathers were radio and television repairmen (11).

During 1968—1975, the annual rate of eye cancer among men who worked in the electrical and electronics industry in England and Wales was consistently greater than that of the general work force. None of the other 25 occupational groups showed consistent increases of comparable magnitude (12).

Vagero and Olin studied whether cancer cases in Sweden reported in 1961–73 contained more cases of cancer among men or women aged 15–64 who were classified as working in the electronics industry (the particular occupations were not specified) (13). They found a 15% excess of cancers among men, and an 8% excess of cancers among women for workers in the electronics industry. Canadian high-voltage powerline workers exhibited more than a three-fold increase in cancer of the intestine ($P < 0.01$) (14).

In 1977 Becker reported a cancer cluster among approximately 1100 residents of a rural area south of Syracuse, New York that was traversed by high-voltage powerlines and contained 20 antennas (15). Cancer incidence during 1974–1977 was almost double the expected rate based on occurrence of cancer in the county as a whole.

In 1979 Wertheimer and Leeper reported the first controlled study of a potential link between electromagnetic fields in the general environment and human disease (16). They asked whether children who lived in the greater Denver area, and who died of cancer in 1950–1973, lived near powerlines more commonly than did normal children. Their definitions of both “powerline” and “near” were arbitrary, and were rooted in their idea that any nexus between powerlines and cancer was mediated by the magnetic field of the powerlines. Their definitions were applied to the addresses of both the children who died from cancer, and to the addresses of an appropriately chosen control group of children. Roughly twice the expected death rates from leukemia, lymphoma, and nervous-system tumors were found in patients living near powerlines. Subsequently they performed a similar study among adults who died (or recovered) from cancer in 1967–1977, and again found an association between living near powerlines and cancer (17). Data for both studies is shown in Table 2.

TABLE 2

Incidence of Cancer Reported by Wertheimer and Leeper (16,17).

	<u>CHILDREN†</u>		<u>ADULTS*</u>	
	Cancer		Cancer	
	<u>Cases</u>	<u>Controls</u>	<u>Cases</u>	<u>Controls</u>
Near Powerlines	101	55	438	372
Away from Powerlines	171	217	741	807

† Birth addresses: all cases

* Wiring subcategories combined

Children, $\chi^2 = 18.20$, $P < 0.001$. Adults, $\chi^2 = 7.94$, $P < 0.01$.

Fulton et al., studied the possible association of childhood leukemia with powerlines in Rhode Island (18). The study was similar in many ways to the study by Wertheimer and Leeper, and differed mainly in the manner in which nearness was defined. Using their definition, Fulton et al., could not demonstrate a link between childhood leukemia and powerlines. Their data was subsequently reanalyzed by Wertheimer and Leeper who applied their definition of nearness, and again an association with powerlines was not found (19).

It is difficult to characterize an ambient electromagnetic environment in engineering terms because of the spatial, spectral, and temporal variations of the fields. In epidemiological studies this difficulty can sometimes be overcome by relating features of the environment, as opposed to actual measurements of the electromagnetic field, to cancer incidence. But since perception of features of an environment is a subjective process, divisions and classifications may not be made in the same fashion by different investigators. Since the design and density

of powerlines varies significantly throughout the country, a classification system that indexes exposure in one area may not do so in another area.

In a case-control study that involved 716 tumors (660 malignant, 56 benign) in Stockholm County (1958–1973) in patients 0–18 years of age (20), the authors asked: (1) did more than the expected number of tumors occur in children who lived near 200,000-volt powerlines; (2) did more than the expected number of tumors occur in people who lived in regions with high magnetic fields? Among the tumor cases, they found 32 dwellings at which a 200,000-volt powerline was visible, but only 13 such dwellings were found in the control group ($P < 0.05$). Of the 48 dwellings that exhibited a high magnetic field (3 mG or greater) 34 were tumor cases and 14 controls ($P < 0.05$).

The two major airports in Wichita, Kansas, use radars to control approaches and landings, and their beams blanket the city. Lester and Moore (21) asked whether the geographic pattern of cancer in Wichita could be related to the radar fields. The variable topography of Wichita was a complicating factor because the hills interrupted the line-of-sight beam of the radars thereby creating a shield from one or both radars in various parts of the city. A three-tiered measure of exposure was derived consisting of areas with the highest, intermediate, and lowest amounts of radar exposure. It was found that cancer incidence in Wichita residents in 1975–1977 (3,004 cases) was related to the amount of radar exposure ($P < 0.05$) after correcting for age, economic stratification, male/female ratio, and race. Those census tracts with the highest shield showed the lowest cancer incidence, and the tracts with the lowest shield had the highest incidence of cancer. One cancer category (Code 170, International Classification of Diseases) which includes malignant neoplasms of bone,

connective tissue, skin and breast was similarly correlated with radar exposure ($P < 0.05$). Most cases within this category were breast cancer. Lester and Moore also reported that counties in the United States that had an Air Force Base had a significantly higher cancer mortality during 1950–1969 than did control counties without an Air Force Base (22–24).

A cluster of five cases of a rare ovarian tumor diagnosed over a 4-year period in northwest Jacksonville, Florida was reported (25). Three potential environmental risk factors were identified in the neighborhood where the children lived: proximity to a major highway, a lead smelter, and powerlines. The children lived 14–592 feet from a 69,000-volt powerline an average of 7.8 years prior to diagnosis.

Evaluation of Epidemiological Data

Each study contains actual or speculative shortcomings that might validly block extrapolation from the observed association (between a particular occupation or residential environment and cancer) to an inferred association (between one particular environmental characteristic and cancer). The study that has been subjected to the most scrutiny of this kind is that of Wertheimer and Leeper (16). It has been argued that:

1. The selection of controls might have been biased (26);
2. Only deceased children with cancer, rather than all incident cancer cases, were studied (27);
3. The electromagnetic field from household appliances was neglected (28);
4. The actual electromagnetic field was not measured (29);
5. The study was not done in a blinded fashion (30).

Based on these criticisms, the authors downplayed or opposed use of the

study to support inference of an association between electromagnetic fields and cancer. Proceeding stepwise through each epidemiological study, the same conclusion might be extended to the corpus of the literature.

We think that the better approach is to judge the studies as a group with regard to the underlying question. Frequently, in a retrospective epidemiological study, the investigator is simply unable to take steps to mitigate potential confounding variables. But when studies are done by different investigators at different times and places using different study groups, the likelihood of a common confounding variable (or other study bias) is proportionately reduced. Thus, the whole is more valuable than the sum of the parts.

Leukemia has been linked to occupations that, in some sense, involve electricity (2–4). Such workers are exposed to many chemicals including diphenyls, naphthalenes, phenols, epoxys, oils, and solvents, any one or combination of which may have mediated the observed link. But most of the electricity—related occupations listed within the individual studies reported more cancers than expected (25 of 32 occupations described in the studies in Table 1). These occupations, which included electrician, aluminum worker, power-station operator, powerline worker, and telegraph operator, have no discernible chemical factor in common. Furthermore, a link to leukemia has appeared in a group formed on the basis of hobby interests (7), thereby lending more credibility to a non—chemical hypothesis. Increased leukemia has been found in children who lived near powerlines (16). Powerlines can produce ozone, but this seems an unlikely explanation for the observed correlation because there were few addresses near the type of high—voltage powerlines that produce ozone. The evidence of a link between leukemia and electromagnetic fields has emerged from

many different places: California, Denver, England, Los Angeles, New Zealand, Wales, and Washington.

If electromagnetic fields are linked to cancer, the nervous system seems likely to be a target. Electrically-exposed civilian workers exhibited higher than expected incidences of brain tumors and eye cancer (9,12). An increase in nervous-system neoplasms apparently occurred among Navy servicemen (8) — a group whose chemical environment was probably different from that of the civilian workers. Among children who live near powerlines in Denver, the death rate from cancer of the nervous system was about twice the expected rate (38.6% vs. 21.1%) (16).

The pattern of elevated disease in both occupational and non-occupational groups seen for leukemia and nervous-system cancers was also seen in overall cancer (13,17,20–22).

From among a collection of epidemiological studies whose individual conclusions are beyond what we normally attribute to chance, we can perceive only one common factor that links cancer with the subjects' environment: the electromagnetic field. The frequency of cancer was increased when the electromagnetic field was added to the environment, and therefore the electromagnetic field was a risk factor for cancer.

There are three additional lines of evidence that add plausibility and perspective to the link between electromagnetic fields and cancer. The possible etiological role of environmental electromagnetic fields in disease was first suggested by Becker in 1972 (31) on the basis that environmental electromagnetic fields produced internal currents and voltages that rivaled in strength those produced naturally by the body. Shortly thereafter, direct evidence from laboratory studies was produced (32). It is now widely accepted that electromagnetic energy can be applied for a variety of therapeutic purposes, particularly involving bone growth. It is therefore not surprising that adventitious

exposure to electromagnetic energy is linked to disease. The surprise would be that electromagnetic energy could be an agent that produced desirable effects in the hands of a clinician, but had no public–health consequences when it was administered in an uncontrolled fashion in the general or workplace environments.

The second point (which we will discuss in more detail in a subsequent Section) is that there is a rich literature dealing with the biological effects of electromagnetic fields. Since the early 1970s (even before that in the Soviet Union) many reports have appeared describing various physiological changes in laboratory animals subjected to electric or magnetic fields or electromagnetic waves. It is now widely accepted that these studies establish the existence of non–thermal, generally adaptive biological effects in animals. Since many of the laboratory studies were done using field strengths that are directly comparable to levels present in the environment, the likelihood that existing environmental exposure patterns might be a health risk we increased.

Finally, following the thread that emerges from the laboratory studies, we must expect that environmental electromagnetic fields will be linked with all diseases, not simply cancer. The laboratory studies show that systemically applied electromagnetic fields are biological stressors, and chronically stressed animal populations are broadly susceptible to disease. The animal studies do not show that the electromagnetic field itself is a mutagenic agent *in vitro* (a property that might lend support to the idea that cancer was a disease specifically associated with exposure to electromagnetic fields). Therefore, based on the laboratory studies, electromagnetic field exposure in the environment should be correlated with increased levels of all diseases, not only cancer. As we shall see below, such

evidence is emerging.

The epidemiological studies do not yield a satisfactory measure of the strength of the link between electromagnetic fields and cancer: perhaps it is small. A link has emerged, in the face of possible methodological shortcomings in individual reports, some of which would obscure any link between electromagnetic fields and human cancer (see criticisms listed above) because they are generally randomizing Influences that tend to make the case and control groups identical — not different. Thus, perhaps the link is strong. Even if the actual magnitude of the link is small, it is of great public—health significance because it is a common risk that affects a substantial part of the population. It would be helpful if the critics of the existing studies repeated them in a manner free of the perceived defects. Unfortunately, none have done so.

III. ROLE OF ELECTROMAGNETIC FIELDS IN CLINICAL CANCER

How are electromagnetic fields related to carcinogenesis? Any answer will require both knowledge of how electromagnetic fields interact with tissue, and a conception of how cancer occurs. Presently, a true understanding of both processes is hidden, but enough is known to permit assembly of a general framework for analysis of the link between electromagnetic fields and carcinogenesis.

Cancer Model

The Model for carcinogenesis that we shall use (Figure 1) seems to us to be the most parsimonious collection of ideas that are consistent with cancer's known characteristics. We do not justify the Model here, but simply state it as a means of conveying our thoughts concerning how electromagnetic fields affect

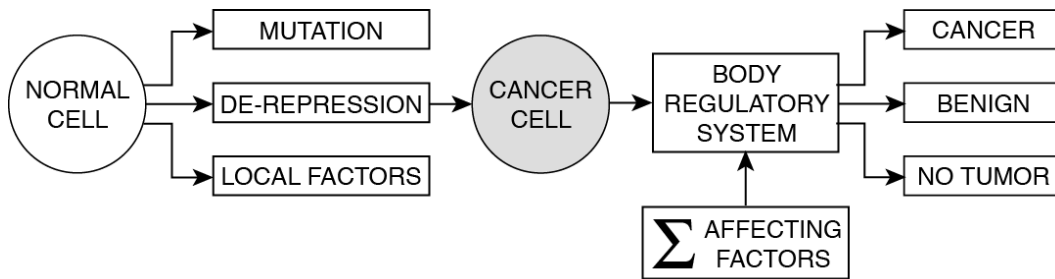


FIGURE 1

Model for carcinogenesis. Factors operating at both the local and system levels are concatenated to produce clinical cancer.

the body.

The causal chain that leads to the development of clinical cancer has several parts. It begins when a normal cell is subjected to a physical agent (or combination, simultaneously or consecutively) that disrupts the genetic machinery, or alters the local factors that regulate growth, resulting in a cancer cell. The transformed cell may itself be a biological dead—end, or it may grow into an observable tumor. The fate of the transformed cell depends on the response of the body's neuroendocrine and immune systems. Any factor that actually impairs the ability of the body's regulatory system to recognize or destroy the cancer cell increases the risk of development of clinical cancer. Systemic factors differ from factors that bring about the normal-cell/cancer-cell transformation mainly in respect to where they physically act on the body, and (presumably) on the quantum of their role in the overall process of the development of clinical cancer.

Role of Fields in Clinical Cancer

Unlike chemicals, the presence of electromagnetic fields in tissue cannot

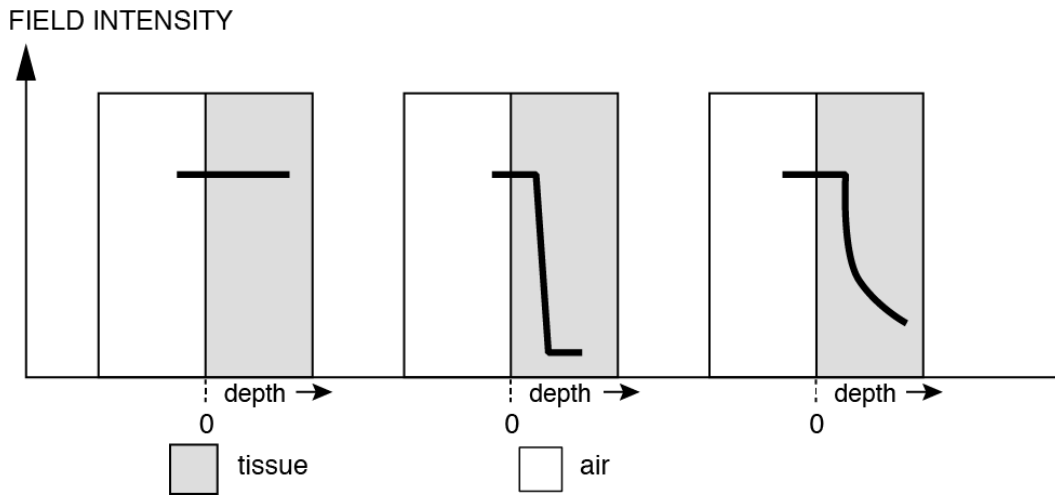


FIGURE 2

Penetration of electromagnetic field into tissue. Only magnetic fields penetrate into the body organs.

be measured directly. The best that can be done is to estimate the strength of the tissue fields based on measurements of the strength of the incident fields, and a computation of the penetration of electromagnetic fields into mathematical models of tissue. Despite the complexity of the various mathematical models (33), the outlines of tissue–field interactions are clear (Figure 2).

The interactions fall into the three broad classes shown in Figure 2. Biological tissue is transparent to magnetic fields and, consequently, an applied magnetic field is also present inside tissue with undiminished strength. An applied electric field causes a charge flow in the skin, that tends to shield the underlying tissue. Typically, the tissue levels are 10^7 smaller than those of the applied field

(34), and the precipitous drop in field strength occurs over skin thicknesses usually no greater than a few millimeters. Electromagnetic waves such as from powerlines (60 Hz), radio (500 KHz), television (1 00 MHz), or microwave ovens (2.45 GHz), usually exhibit an exponential decay in strength with distance of penetration into tissue. The actual penetration depth depends on the electrical properties of the tissue, and the frequency of the electromagnetic wave. A typical computed penetration depth at 60 Hz is 9 cm, and at 100 MHz it is 0 .01 mm. Thus, with the possible exception of magnetic fields, the body's detection system for external electromagnetic fields probably exists within the first few millimeters of skin and underlying tissue.

In some environmental–exposure patterns, such as those involving magnetic fields from high–voltage powerlines or airport metal–detectors, electromagnetic fields have the potential to act directly on the cell or on the local cell environment because they are physically present in the target tissue — like asbestos in lung cancer. The clinical use of electromagnetic fields for treating disease is hypothesized to act in exactly this manner. When electromagnetic energy is applied locally via tissue–penetrating magnetic fields (35) or percutaneous wires (36) cells can be stimulated, resulting in therapeutic consequences. But the epidemiological studies have linked all electromagnetic fields, not simply the tissue–penetrating magnetic fields, with clinical cancer. This suggests that the link between electromagnetic fields and human cancer is mediated systemically because, in most instances, the electromagnetic fields are not present in the tissue and therefore cannot cause a normal–cell/cancer–cell transformation by directly affecting a cell. The prototypical chain of events therefore must involve detection by the nervous system of a change in the external

electromagnetic environment, and a subsequent cascade of consequential changes in the nervous system itself, in its connections with the endocrine and immune systems, and in the functional status of those systems. The chronic initiation of this chain-of-events adversely affects the efficiency of the body's regulatory system, thereby increasing the likelihood that aberrant growth will go unchecked.

IV. MECHANISM OF ACTION

Since electromagnetic fields are linked to clinical cancer via their ability to adversely affect the body's surveillance system, a variety of biological effects should be demonstrable in laboratory animals exposed to electromagnetic fields. For fields to produce systemic biological changes, their presence must be detected by the central nervous system, and consequently there should be changes in appropriate measures of central-nervous-system activity. If fields act via the body's control systems, changes in immune-response and endocrine parameters ought to be detectable. Since changes in these systems — however produced — can have many consequences, effects in other physiological endpoints should also occur. Each of these classes of biological effects has been described in numerous studies.

Electromagnetic fields caused a variety of structural neuronal changes in the brains of exposed rabbits including alterations of the endoplasmic reticulum in Purkinje cells, and the formation of numerous lamellar bodies (37). Rabbits briefly exposed to electromagnetic fields exhibited altered brain-wave activity, and the nature of the changes depended on the particular animal (38): in a series of 24 rabbits, 14 rabbits exhibited depressed activity originating in the cortex

(compared to pre-exposure base-line), 6 animals exhibited elevated activity, and 4 animals exhibited no change. Electromagnetic fields altered the innate orientational ability of birds (39,40). Electromagnetic fields with signal characteristics intended to mimic those of typical radars altered the effects of a drug on the behavior of trained rats (41).

Rabbits chronically exposed to an electromagnetic field exhibited reductions in peripheral blood granulocytes, depressed lysozyme activity, and depressed granulocytosis following bacterial challenge (42). When rats were exposed to electromagnetic fields, the percentage of peripheral lymphocytes capable of being stimulated by phytohemagglutinin was significantly reduced (43). Mice exposed to electromagnetic fields and then challenged with foreign red-blood cells exhibited a depressed immune response (44).

Rats continuously exposed to electromagnetic fields for 30 days showed lower average serum levels of corticoids, and larger pituitaries (45). Sixteen tumors occurred in 100 chronically-exposed rats, compared to 4 tumors found among the 100 control rats (46). Seven endocrine cancers and 6 pheochromocytomas (benign adrenal tumors) were found among the exposed rats, compared to only 1 endocrine cancer among the controls. Exposure of monkeys produced an increase in urinary corticoids which lasted about 6 days, after which the corticoid levels returned to baseline despite continued exposure to the field (47). In another study, a similar effect on corticoids in rats persisted for 4 months (48).

Exposure to electromagnetic fields delayed fracture healing in rats (49), altered growth in rats (50) and monkeys (51), produced skeletal abnormalities

in chick eggs (52), and promoted cancer (53–55) and mutagenic changes (56).

Various blood indices have been shown to be sensitive to a change in electromagnetic environment (57), and similar environmental changes have been shown to produce alterations in human subjects involving serum triglyceride levels (58), circadian rhythms (59), reaction time (60), and performance on standardized tests (61).

The world literature dealing with electromagnetic–field–induced changes in laboratory animals has been reviewed (62). The reports can be summarized this way:

- (1) Exposure to electromagnetic fields can result in alteration of the metabolism of all body systems, including the nervous, endocrine, cardiovascular, hematological, immune, and reproductive systems;
- (2) The effects manifested in each tissue or system are largely independent of the type of electromagnetic field in the sense that common physiological responses are produced by spectrally different electromagnetic fields;
- (3) An organism's response to an electromagnetic field is determined by a combination of factors including its physiological history, genetic predisposition, and the totality of prevailing environmental conditions;
- (4) Electromagnetic–field–induced biological effects in animals are best characterized as adaptive or compensatory because the fields present the organism with an environmental factor to which it must accommodate. Simple dose—response relationships are generally not observed.

The animal studies show that an electromagnetic field can be a

biological stressor, by which we mean that it can elicit an adaptive response. It is self-evident that the ability to adapt to chronic stressors is finite, and that the addition of any chronic stressor tends to make it more likely that the subject's ability to cope will be exhausted — a condition manifested clinically as disease. Thus, environmental electromagnetic fields tax adaptive capacity, and it is this characteristic that links them with human cancer.

The idea that non-traumatic non-heritable disease occurs when the total physiological load caused by external stressors exceeds the body's ability to adapt or cope has previously been expressed by many authors in a variety of contexts. The idea, however, seems perpetually novel because relatively little epidemiological data has been produced to support it. This may be mostly a result of the difficulties in performing epidemiological studies. The emergence of an epidemiological correlation between electromagnetic fields in the environment and cancer is largely a consequence of the fact that, as a society, we maintain adequate statistical records regarding cancer incidence. The studies should not be viewed as implying that cancer, as opposed to any other disease, is a more likely manifestation in the chronically-exposed population. Electromagnetic fields have been linked with suicide (63), polycythemia (64), nervous system disorders (65,66), sexual dysfunction (67) and fetal development (68), and future studies will undoubtedly link it with other diseases. The electromagnetic field is a potentiating factor for all diseases because it is one of a milieu of neurogenic and somatic stressors.

In animal studies, physiological variables that sample adaption — endocrinological endpoints, for example — typically return to baseline values despite the continued application of the stressor. It might be argued that, in such a

subject, since no specifically measurable physiological parameters can be used to discriminate between the adapted state and that of a comparable naive control subject, the two subjects should be viewed as physiologically identical, and therefore at identical risk for developing clinical disease. We think that the better view is to regard the two states as quite distinct, and as being associated with different propensities for the development of disease. This view is based partly on the results of numerous animal experiments showing that animal populations subjected to one stressor exhibit greater susceptibilities to a second concurrent stressor, as compared to the susceptibility manifested in the absence of the first stressor. This view is also consistent with general clinical experience that patients fare better when identifiable stressors — both neurogenic and somatic — can be identified and eliminated.

V. SUMMARY

Chronic exposure to a biological stressor is a risk factor for disease. Laboratory studies clearly show that electromagnetic fields can be biological stressors, and that such fields, when present in the environment, are therefore risk factors for disease. The emergence of direct evidence of a link between electromagnetic fields and one class of diseases — cancer — has been facilitated by the availability of cancer data, and does not imply that electromagnetic fields have a particular propensity to promote cancer as opposed to heart disease, psychiatric disorders, or other maladies. Controversy, or at least the appearance of controversy, regarding the health risks associated with environmental electromagnetic fields has developed (69,70) because the emerging scientific

picture runs markedly counter to the long-standing interests of some industries and government agencies in unbridled use of the electromagnetic spectrum. The significant fact is that the existence of a link between electromagnetic fields in the environment and disease has been established. Despite the fact that many important details regarding it remain undiscovered, there is one obviously appropriate interim response: Minimize exposure.

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