Environmental Health Perspectives
Vol. 75, pp. 159-171, 1987

Electromagnetic Fields and Public Health

by Timothy E. Aldrich,*† and Clay E. Easterly*

A review of the literature is provided for the topic of health-related research and power frequency electromagnetic fields. Minimal evidence for concern is present on the basis of animal and plant research. General observation would accord with the implication that there is no single and manifest health effect as the result of exposure to these fields. There are persistent indications, however, that these fields have biologic activity, and consequently, there may be a deleterious component to their action, possibly in the presence of other factors. Power frequency electromagnetic field exposures are essentially ubiquitous in modern society, and their implications in the larger perspective of public health are unclear at this time. Electromagnetic fields represent a methodological obstacle for epidemiologic studies and a quandary for risk assessment; there is need for more data.

Introduction

In 1984, Americans consumed an estimated 780 billion kilowatt-hours (kWh) of electrical power; by the year 2000, usage is forecast to be 1320 billion kWh. This projection is based on the trend in the sale of electricity (Fig. 1). In 1983, the average American household used about 9000 kWh and had an average annual electricity bill of $666. Forecast for the year 2000 will be an average annual household usage of about 10,671 kWh at a cost of some $1132 (*1*).

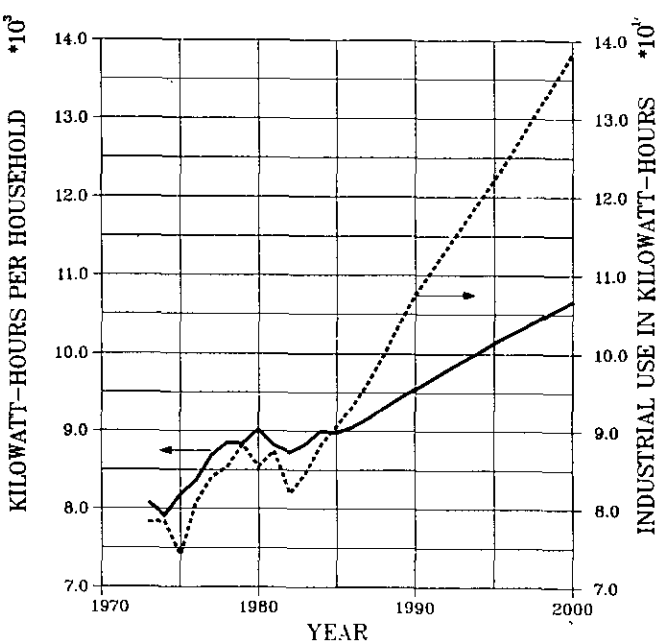

FIGURE 1. Electrical energy use in the United States (*1*).

Along with this energy-related evidence of our productive society, there has been an increasing concern over health risks associated with exposure to electromagnetic fields. The exact nature (frequency, intensity, schedule, etc.) of the exposure is uncertain at this time. Although many biological test systems have been reported to exhibit responses from exposure to electromagnetic fields, the basis for most of the public health concern arises from the ubiquity of the exposure rather than the severity of the response.

Electric and magnetic fields are present during the generation, transmission, distribution, and end use of electrical energy. The dominant frequency is 60 Hz (Hertz, cycles per second), which is the frequency of household fields. Electric fields are present whenever electrical lines are energized, but magnetic fields occur only during the flow of current (as when power is being used). Low-level electrical and magnetic fields are produced by home appliances, lighting fixtures, TV sets, etc. Both fields can radiate through air and other media; however, some shielding is afforded by a variety of factors, including trees, hills, and buildings (*2*).

Electromagnetic fields come in a wide range of energies per unit package. The package known by the physicist's term, the quantum, is the smallest unit of transmissible energy. Strings of these packages travel through space at the speed of light. At the highest energy end of the electromagnetic spectrum are the gamma rays, which have frequencies greater than 10^{16} Hz. The lowest energy end of the spectrum approaches 0 Hz. The eye is the only universally recognized human receptor for electromagnetic fields; the human eye can see quanta of energy from 4.3×10^{14} Hz up to about 7.5×10^{14} Hz. Many animals have special receptors for

*Health Effects and Epidemiology, Health and Safety Research Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831.
†University of Texas School of Public Health, Epidemiology Research Unit, Houston, TX 77025.

electric or magnetic fields that aid them in navigation or detection (e.g., birds). Figure 2 depicts the electromagnetic energy spectrum and its sources (*2*).

The two classic types of biological injury that may occur from exposure to electromagnetic fields are ionization and heating. Ionization (the formation of charged particles) occurs at the higher end of the energy spectrum (X-rays). Ionization can result in the rearrangement of important genetic material and nongenetic material, leading to cell death or mutation. Heating occurs at the lower end of the energy spectrum (infrared, microwaves) and can be more or less harmful, depending on the degree of heating that occurs (Fig. 2). For the 60-Hz fields of interest in this article, the available energy per quantum is far from being able to produce ionization.

To produce a heating rate of 1 W/kg (like that occurring naturally due to life processes in a normal human body), electric fields in air would have to be between 10^7 and 10^8 V/m, or magnetic fields would have to be between 1 and 10 tesla (T). Electric fields greater than 10^6 V/m cannot be maintained in the air (spark discharge occurs), and magnetic fields in the 1- to 10-T range are found only in special scientific or medical applications. Maximum electromagnetic field strengths under high-voltage transmission lines are between 1×10^3 and 15×10^3 V/m, and 1×10^{-5} or 5×10^{-5} T. These values are quickly reduced as one moves further from the transmission lines. The heating effect of standing under the highest voltage electrical lines in the United States (765 kV) is 100 million times smaller than natural metabolic heating (*3*). Thus, any observed biological effects that may result from exposures to electromagnetic fields must evolve from more subtle mechanisms than gross ionization and/or heating.

A number of biological systems have been found to be perturbed by exposure to extreme low-frequency (ELF) fields. Whether such responses represent a significant influence on the health and well being of the organism is not yet clear (*4*). If important influences are found to occur, several questions will follow logically. What type of exposure (field strength, duration, time sequence) may be required to elicit the response? Then, who will make up the population at risk for these effects?

Background

In the late 1960s, reports came from Russia suggesting that workers in electrical substations were experiencing various (acute) symptoms that might be related to their occupation (*5–7*). These early reports were disparaged because of profuse methodological weaknesses (e.g., no comparison groups, small numbers of subjects, subjective reporting) (*7,8*). A few electrical companies in other countries made surveys of their workers' clinical well being and found no basis for further concern (*8–10*). Since 1979, a number of reports have been published suggesting that there may be chronic health effects associated with exposure to electrical fields. The end points most often in question are cancer and birth defects (*11–15*).

The debate over possible health effects associated with exposure to electromagnetic fields has been influenced notably by three other items of information:

Animal research has been commissioned by several agencies, most actively by the U.S. Department of Energy, the Electric Power Research Institute (*14*), and more recently, the New York State Department of Health. This research has failed to demonstrate consistent evidence of deleterious health effects from electromagnetic field exposures to experimental systems. For that matter, in many experiments, no difference was observed between experimental and control groups. The research has provided some information about possible mechanisms of action by these fields, yet the exposure conditions and biological end points studied are not advantageous for comparisons with human exposure conditions.

Only recently have efforts been initiated to measure the complex ELF electromagnetic field exposures that comprise modern human experience. Considerable work has been completed with scaling ELF fields to permit better characterization of comparable exposures between humans and test animals (*16*). However, considerable development is still anticipated with the development of technology for monitoring complex human exposures to the myriad sources of ELF fields (*17–19*).

Considerable public debate has occurred over the construction of several extremely high-voltage transmission lines in various parts of the United States and Canada. Transmission lines move electrical energy di-

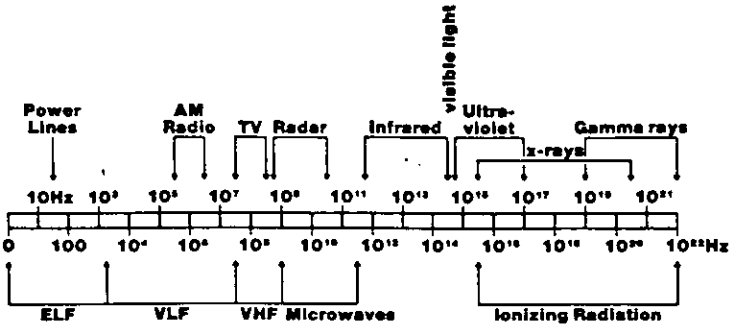

FIGURE 2. The electromagnetic spectrum (*2*).

rectly from its generation to a point (substation) from which it is then distributed to consumers. The movement toward higher voltage lines is because of efficiency considerations; simply, high-voltage lines carry more electricity and do so less expensively (*14,20*). Table 1 demonstrates the recent growth in the higher voltage more-efficient transmission lines.

Notwithstanding the higher voltages represented by the newer transmission lines, the public is literally bathed in a sea of 60-Hz waves. Additional electromagnetic field exposures include frequencies used to transmit information (radio, television) (Fig. 2). Restricting attention only to power frequency (60 Hz), however, we find that only a few individuals live near the very high-voltage transmission lines (345 to 765 kV). More live near the medium-voltage distribution lines (69 to 230 kV); more still live near residential (small) distribution lines (26 kV), and essentially everyone is near 120 V lines (household levels).

Currently, when considering all sources of information on the topic of effects from electromagnetic fields, no clear public health impact is evident. However, as laboratory and human studies continue to investigate the level of concern (level of risk), the prudent public health response would be to identify all possible populations at risk. The process of defining population exposure conditions is just beginning. The simple ubiquity of the exposure (at some degree, low or high) argues for further investigations.

Literature Review

Experimental Studies

Investigations on cellular and nonhuman test systems to date have been very sophisticated and quite successful in meeting their objectives. The elimination of possible environmental artifacts, such as noise, vibration, and microshock, has improved the present generation of data compared with that reported in the early and mid-1970s (*22*). Significant achievements have also occurred in the production of exposure conditions that are well characterized and nearly uniform. These advances in exposure-related technology were necessary, because basic research has focused on studying the biological activity resulting from very specific exposure conditions (*23*). The exposure conditions have usually involved a constant field strength for a prolonged time (*22*). The duration of exposure varied across experiments, as did permutations of intensities. The 60-Hz frequency was most often used, and with field strengths to simulate maximum exposure conditions under transmission lines. Initial attention was focused on the electrical component of the fields alone. Engineers went to great lengths to minimize the magnetic fields (*23*). Recently, the magnetic component has been used in some experiments, either alone or in combination with electric fields.

Table 1. New lines (overhead only) and substations energized, percent change (1983–1984) (*20*).

Transmission lines	% Increase
345–765 kV	65
69–230 kV	2
Substations	14

In Vitro. Studies with prokaryotic cell lines (e.g., conventional Ames testing) have all been negative; that is, there was no evidence of mutagenicity from electrical fields (*24,25*). Some studies have been made with cells from the mollusk and other lower species; these gave considerable evidence of transport effects on cellular membranes by electrical fields (*26–28*). Studies involving eukaryotic cells (e.g., rat, mice, and Chinese hamster ovary cells) have shown marginal effects that were interpreted very cautiously. The observed effects involved: calcium ion transport across cell membranes; DNA synthesis, cell division, and growth rates; neuroregulator cells (levels of cyclic adenosine, monophosphate, and pineal melatonin and serotonin); growth characteristics in bone cultures; and chromosomal breaks, dicentrics, etc., but no increase in sister chromatid exchanges (*29–43*).

Two studies on human lymphocytes and one with bovine lymphocytes exposed to electromagnetic fields *in vitro* have yielded conflicting evidence. One of the studies of human cells showed no consistent difference for exposed versus nonexposed cultures (*44*). The other study of human cells found perplexing changes in protein kinases (cellular enzymes) at certain frequencies and durations of exposure (*45*). Recent reports from this latter research have elaborated the role of calcium transport with protein kinase activity and suggested a potential for disruption of intracellular communications via a calcium pump mechanism (*46*). This provocative hypothesis is being studied at this time. Evidence from the bovine lymphocyte study suggests increases in chromosome breaks, but without concurrent increases in sister chromatid exchanges (*43*). The findings of several researchers even suggest the possibility of an effective window, wherein only specific combinations of frequency, intensity, and duration may result in the measurable effect (*29,33,43*). Such indications of subtle cellular effects led to a study of secondary cancer promotion effects using a 60 Hz, pulsed, 20-G (gauss) magnetic field. This experiment involved exposure of three myeloid leukemia cell lines, with a phorbol ester as the primary promoter; no effect was seen from the magnetic fields (*47*).

Studies of human tumor cells exposed to electric and magnetic fields, and of fibroblasts exposed to magnetic fields alone, have revealed modifications in growth patterns and increased DNA synthesis (*34,48*). The suggestive findings with transformed (or mutated) cell lines, some of which involved interaction with a magnetic component, give researchers pause in interpreting the findings of cellular data (*26,30,35,47*). The small-scale and sporadic nature of the effects seen with electromagnetic fields raises questions about the importance of specific frequencies, intensities, and treatment schedules, and

possible interaction with the earth's static magnetic fields.

Research with Mice. Several researchers have studied the effects of ELF fields on mice; most experiments have been with pure electric fields, but a few have been with electric and magnetic fields. One difficulty with interpretation across these studies is that various intensities were used. Of seven studies reviewed with only an electrical field component, one did not report the intensity, and the others used 240, 15 and 50 kV/m, 80kV/m, 100 kV/m, 100 to 130 kV/m, and 10 kV/m, respectively. Each study used a different time course in the life of the animals with respect to exposure; however, in all cases, the fields were constant during exposure, usually about 20 hr/day (*49–56*). The murine studies were investigations of germ cell effects, biochemistry, and cell counts (or circadian cycles). None of the studies specifically addressed end points such as cancer or birth defects. Virtually all the results (neuroendocrine, growth and development, reproductive, etc.) indicate no adverse effects. Several studies by Marino (*57–59*) suggest increased body weight gain, higher weights for specific organs, and elevations in certain circulatory hormones among mice exposed to low-frequency electromagnetic fields. Findings in murine systems have been questioned because of weaknesses in the study procedures (e.g., spark discharges, bristle vibration, gradients in the fields, small numbers of animals) or shifts in circadian phases (*15,56,60*).

Research with Rats. Most of the rat experiments with ELF fields have been with pure electrical fields; a few have been with both electric and magnetic components. Hilton and Phillips (*61*) found no evidence of increases in growth or metabolism for rats exposed to 60 Hz electrical fields versus nonexposed animals. In a similar study, Free et al. (*62*) likewise found no effects on body weights or hormone levels in the plasma; they attributed any apparent differences seen between the exposed and nonexposed animals to a phase shift in the normal cyclic variation of different hormones. Most of the rat investigations considered either behavioral effects or effects on the neuroendocrine transmitter system (especially serotonin and its metabolites) (*63–67*). Differences in experimental groups were small and not consistent across exposure conditions; the possibility of an effective threshold has been speculated (*36,38,63,68*).

As in mouse research, much of the early work was confounded by experimental artifacts; small sample sizes were used, and no manifest effects were detected. An exception to these limitations and marginal results are two studies by Jaffe et al. (*69,70*). In these studies, there was consistent, statistically significant evidence that an ELF field effect would enhance synaptic transmission (peripheral nerve function) and neuromuscular function (*69,70*). One experiment with rats was conducted to replicate an experiment with swine (see next section) that indicated a change in fertility and/or birth defects (*64,68*). The infertility was associated with the second generation of animals; birth defects were associated with the second breeding capability of the F_0 generation. Rats displayed a similar response for birth defects, but not for decreased fertility. This study with rats has led to proposed plans for a replicate rat breeding study (*64,68,71*).

Other Whole-Animal Systems. The principle line of inquiry with animal research was based on the *a priori* knowledge that ELF exposure (electric and/or magnetic fields) would not result in overt clinical effects. Further, the role of these fields in nature was believed to be largely regulatory (e.g., circadian rhythms) and behavioral (e.g., perception). For these reasons, bees were a logical choice for study subjects. Research with bees has led to some interesting observations. When hives are placed in strong electric fields, currents and voltages are induced in the hive that are dependent on field strength, hive characteristics, and moisture conditions. Under a variety of conditions, honey production can be reduced and various hive activities may become erratic. Two categories of mechanisms appear to be responsible. One is from electrical shock from induced fields in the body of the bee; the other mechanism is related to direct exposure to electric fields (*72*). There are two simple solutions to the problem of hive disruption. One is to avoid keeping bees in high-field regions near the right-of-way of high-voltage transmission lines; the other solution is to place grounded metal screens over the hives (*73*).

Rabbits were studied indoors with 10 kV/m fields and outdoors directly under high voltage distribution lines (*74*). Each of these investigations failed to demonstrate any consistent effects from these constant fields, even for protracted periods (e.g., 9-months exposure). The rabbits exposed outdoors showed some transient delay in growth, but this was not replicated indoors. The transient retardation in growth was based on qualitative judgments of cerebellum development. Morphologic changes in glial cells were attributed to effects on regulatory enzyme systems (*74*).

Chicks exposed to 15 and 25 kV/m fields gave evidence of some transient growth retardation (*64*). Delgado et al. (*30*) found developmental abnormalities in fertilized white leghorn eggs exposed to pulsed magnetic fields. The magnetic field intensities were 0.12, 1.2, and 12 μT, with repetition rates varying between 10 and 1000 Hz. The results were interpreted as indicating an intensity window around a 100 Hz frequency, with 1.2 μT magnetic fields (*30*). Efforts to replicate Delgado's work are in progress.

Miniature swine presented a particularly strategic animal system for ELF research because of their somatic weight and gestation characteristics (*75*). Female pigs were exposed to 30 kV/m electrical fields daily for 20 hr/day throughout gestation. No discernible effects were observed with the first breeding of the animals; however, the F_1 generation gave evidence of decreased fertility. The F_0 generation had an increase in malformed fetuses during their second breeding. The scale of these effects was about twofold between the exposed and nonexposed groups (*75*). This doubling of event frequency in exposed animals is a relatively small effect

when the event is rare (e.g., birth defects). The scale of effect indicates a need for research with large animals (e.g., related to costs for sufficiently large numbers of subjects) and human populations.

Plant and Free-Roaming Animal Research. Crop effects have been one element in the right-of-way debate concerning high-voltage transmission lines. Research on grains growing under high-voltage transmission lines is currently in progress (*76*). Research with very high electrical fields (equivalent to about 1000 kV/m in air) showed variable effects (none, increase, decrease) on root systems of different plants (*77,78*). Several varieties of trees showed no effect from exposure to high-intensity transmission lines; however, Douglas fir trees growing near the lines experienced less growth, primarily resulting from shoot tip dessication via corona and microdischarges (*76*). Studies are just beginning on foraging and growth factors in cattle and elk (*76*). Reports of decreased production among dairy cattle had been one of the more publicized issues; however, this has been explained by spark discharges from improper grounding of electrical milking equipment (*79,80*).

Nonhuman Primates. The ELF field experiments reported here are still in progress. Each of the experiments used very few subjects exposed to continuous electromagnetic fields (under 40 kV/m and from 0.1 to 2.0 G). The health end points studied were behavioral or developmental. Transient reduction of CNS development and small decreases in response levels on behavioral activities were observed with monkeys (*81*). One squirrel monkey demonstrated a lengthening of its circadian light phase following prolonged exposure to electromagnetic fields (*82*). Male rhesus monkeys demonstrated increased growth characteristics that could not be accounted for by the elevation in testosterone levels (*83*). Baboons are being observed for changes in behavior and performance on selected tests in the presence of 60, 100, and 130 kV/m continuous electrical fields. No differences in behavior have yet been defined between the study groups (*84*).

Humans. Two ELF experiments have been performed with human volunteers. A first study (in England) involved direct exposure to 36 kV for 5.5 hr; no effects were found in behavioral or clinical studies (*85*). In an American study, college students served as their own controls for exposure to a 9 kV/m electrical field with a magnetic component applied for 6 hr. Effects were measured with a battery of behavioral tests and many biochemical studies. Only 12 subjects have been used thus far in the study; intermediate findings were statistically significant for effects on heart interbeat intervals, lymphocyte levels, and differential lymphocyte counts (elevated levels of helper T-cells) (*86,87*).

Epidemiologic Studies

Epidemiology is a discipline in which researchers seek to quantify the association of a risk factor (e.g., exposure to electromagnetic fields) with some adverse health event. As epidemiology is the study of disease occurrence in human populations, there are often constraints on the detail of information available for exposures that are quite dissimilar to those experienced in animal studies. This is simply because free-moving humans (in contrast to the carefully exposed volunteer studies just described) have many sources of ELF field exposures that are not consistent either in terms of field strengths for electric and magnetic fields or frequency modulation (i.e., not all are pure 60 Hz) (*88*). The ELF fields also are not maintained for any regular periods of time (hours, minutes, seconds). This leads to weak exposure classification for epidemiologic studies, particularly since humans have many other exposures that must be considered as risks for disease (e.g., smoking, job-related exposures). All of this notwithstanding, epidemiologic studies often provide useful hypotheses for testing with laboratory research and more powerful epidemiologic methods (*88*). The studies cited here are of the hypothesis-generating type. Alone or in isolation, findings of these studies are frought with individual weaknesses. However, if different study populations show consistent effects (Table 2), then this fact argues for further research directed toward testing the hypothesis or providing evidence for or against biological plausibility.

Occupational and Community-Based Studies. Following the early Russian reports of subjective distress from electrical fields, several clinical studies were performed on electrical substation workers in Spain and Canada. No statistically significant health effects were observed, and subjectively reported gastrointestinal symptoms and anxiety were found to be associated with spark discharges and noise from the energized lines (*9,10*). A later study in Sweden, using age-, race-, and sex-matched comparison subjects and larger numbers of workers, found no effects on clinical testing; however, there were fewer male children among families of the exposed workers (*89*). Stopps and Janischewsky (*90*) found no clinical differences between exposed and nonexposed substation workers.

Also in 1979, findings were published from an exploratory study that used death certificate information (1946–1973) for children in the Denver, Colorado, area. Each of 344 pediatric cancer death certificates was matched by age, race, and sex with a comparison death certificate. The exposure criterion of the investigation was residential proximity to particular electrical wiring configurations that were ranked by current-carrying capacity and distance from the residence. The authors interpreted this exposure measure as a surrogate for the variation in magnetic field exposure that may exist within the residences. They also postulated various other factors that could be involved with the indoor exposure (e.g., wiring patterns, multiple and sometimes inefficient grounding). The investigation revealed an elevated occurrence in the high-current configuration group for all pediatric cancers, leukemia, and tumors of the nervous system (risk estimates of 3.2, 3.0, and 2.4, respectively, may be calculated from the data) (*91*).

A replicate study was conducted in Rhode Island,

Table 2. Epidemiologic studies of ELF fields: some calculations.

Lead author	Reference	End point	Risk level[a]	Confidence limits[b]	Power for a risk of 2.0[c]
Milham	(*106*)	Leukemia	PMR = 1.37	(1.12–1.67)	< 0.99
		Acute leukemia	PMR = 1.63	(1.14–2.25)	< 0.99
Wright	(*107*)	Leukemia	PIR = 1.29	(0.85–1.88)	< 0.99
		Acute leukemia	PIR = 1.73	(0.93–2.93)	< 0.91
		Myeloid leukemia	PIR = 2.07	(1.02–3.75)	< 0.85
McDowall	(*109*)	Leukemia	PMR = 1.25	(0.65–2.19)	< 0.88
		Myeloid leukemia	PMR = 1.79	(0.66–3.88)	< 0.65
		Acute myeloid leukemia	PMR = 2.31	(0.61–6.00)	< 0.49
		Myeloid leukemia	OR = 2.1	(1.24–3.59)	< 0.97
Coleman	(*108*)	Leukemia	PRR = 1.17	(0.95–1.44)	< 0.99
		Myeloid leukemia	PRR = 1.23	(0.81–1.80)	< 0.99
Vagero	(*99*)	Larynx	RR = 1.46	(1.05–2.03)[d]	< 0.99
		Lung	RR = 1.52	(1.35–1.72)[d]	< 0.99
Nordstrom	(*98*)	Birth defects	OR = 3.24	(1.28–8.22)	< 0.99
Swerdlow	(*110*)	Ocular cancer	PRR = 2.40	(1.21–4.33)	< 0.95
NIOSH	(*111*)	Brain cancer	PMR = 1.95	(0.95–3.49)	< 0.62
			OR = 1.40	(0.38–5.50)	< 0.16
Lin	(*112*)	Brain cancer	PMR = 2.78	(1.65–4.39)	< 0.99
		Brain cancer	OR = 2.15	(1.07–4.32)	< 0.99
Pearce	(*112*)	Leukemia	OR = 1.70	(0.97–2.97)	< 0.55
Milham	(*113*)	Leukemia	PMR = 1.91	(1.22–2.84)	< 0.90
		Myeloid leukemia	PMR = 2.89	(1.61–4.55)	< 0.63
Spitz	(*100*)	Neuroblastoma	OR = 2.13	(1.05–4.35)	< 0.78
Gilman	(*101*)	Leukemia	OR = 4.16	(1.04–6.18)	< 0.64
		Acute leukemia	OR = 2.71	(0.82–9.90)	< 0.30
		Myeloid leukemia	OR = 3.75	(0.98–22.95)	< 0.22
Calle	(*115*)	Leukemia	PMR = 1.86	(0.99–3.18)	< 0.59
		Acute leukemia	PMR = 2.57	(1.11–5.06)	< 0.31

[a] OR, odds ratio; PMR, proportional mortality ratio; PIR, proportional incidence ratio; PRR, proportional registration ratio; RR, relative risk; SMR, standardized mortality ratio.
[b] As per Haenszel et al. (*130*) and Schlesselmann (*131*).
[c] Assumes one-tail test with $\alpha = 0.05$; power = 1 β as per Beaumont and Breslow (*132*) and Schlesselmann (*131*). Power is the ability of a study to find a certain level of risk if it truly exists in the study population. The number of study subjects is a principal concern with this probability.
[d] Published confidence intervals using a stratified chi-square and Miettinen's form (*133*).

using death certificates of 119 pediatric leukemia cases (1964–1978) and age-, race-, and sex-matched birth certificates for selecting two comparison subjects per case. Residential proximity to a certain electrical wiring configuration was coded in a manner similar to that used in the Denver study. No significant associations were reported; a risk estimate of 1.08 was cited (*92*). The criteria for classification of exposure and the selection of comparison persons were questioned by the Colorado authors. Their recoding of the Rhode Island data resulted in a larger risk estimate (1.36) that was not statistically significant (*93*).

A group of Swedish investigators also endeavored to replicate the Denver findings using childhood cancer data from the Swedish Cancer Registry (1958–1973). The study subjects were matched by age, race, sex, and community of birth. These researchers visited over 2000 residences for 716 case and comparison pairs. Exposures were based on residential proximity to various high-voltage devices (e.g., transformers, electrical railways) and power lines. Their conclusions indicated support for the Colorado study. Calculations with their published data were awkward because of the format for presentation, but with certain assumptions, risk estimates are in the range of 1.4 to 2.5 (*94*).

In 1981, the Colorado authors published results from a study of adult cancer, again using residential criteria to infer ELF field exposure from neighborhood sources (e.g., distribution line configurations). This study contained many design differences intended to address criticisms of their earlier study. Living cancer cases were included, a blinded recoding of their exposure data was made, and extensive stratified analyses were performed for age, urbanicity, socioeconomic status, and neighborhood. A total of 1179 cases were studied, with matching by age, race, and date of death (as appropriate).

Cancer for all sites was reported, although the authors indicated some site-specific variations. The study presented evidence for a dose-response relationship between exposure and cancer and for an induction interval of 7 to 9 years following location in the study area. The authors discussed their results in the context of electromagnetic fields as promoters of cancer (*95*). From the published data, a risk estimate of 1.4 for all cancers may be calculated for exposure to high current configurations.

During this same time, two studies from England reported a relationship between suicides and residential electromagnetic fields. The first study was an ecologic comparison of mortality data in selected British communities with calculated electromagnetic field intensities from overhead, high-voltage electrical lines. The study analysis used conventional correlation techniques to generate the hypothesis of the relationship (*96*). The second study used actual measurements of magnetic fields outside the residences of the suicide victims (death certificate address) and comparison residences. Study subjects (598 subjects) were matched by age, race, and sex to comparison individuals, and extensive comparisons of the residences were made for differences by socioeconomic, urban, and other factors. Elevations in suicide occurrence were small but statistically significant. A risk estimate of 1.5 is calculable for the upper end of the fields measured (10^{-7} T and higher) (*97*).

Two occupational epidemiologic studies from Sweden have described health effects in relation to electromagnetic field exposure. They contain several differences from those reported thus far. First, a retrospective questionnaire study was used with substation workers to consider reproductive effects (*98*). An increase in all birth defects was found for conceptions that occurred during the time that fathers worked on high-voltage systems. Pregnancies from time periods of other work activities were used for comparison purposes. The published data from this report may be used to calculate a risk measure of 3.2 (*98*). The second Swedish study, in 1960, used a historical cohort design with workers in electrical occupations (*99*). Follow-up of the study population from 1960 through 1973 led to risk estimates of 1.5 for both pharyngeal and lung cancers. This study used data from the Swedish Cancer Registry and a national occupational data base; despite this, the number of cancer cases was small (*99*).

The results of a large case-comparison mortality study of pediatric neuroblastomas in Texas were recently reported (*100*). Birth certificates of all children dying of neuroblastoma between 1964 and 1978 were reviewed; two comparison birth certificates were selected from the same year of birth. Paternal occupations were studied using a computerized software package for linking exposures to job titles. The comparability of cases and comparison of subjects were verified for sex, urban or rural, maternal and paternal age, duration of prenatal care, and rate of illegitimacy. Job titles classified as being associated with electromagnetic field exposures gave an odds ratio of 2.1; the odds ratio for fathers reported as electronics workers was 11.7 (small numbers were involved with this category). Not all of the jobs with electric or electrical in the title were exclusively linked to electromagnetic field exposure. Spitz and Johnson (*100*) raise the question about other possible exposures with these jobs that might explain an increase in disease risk, such as dusts, fumes, and hydrocarbon exposures.

A case-comparison analysis of leukemia deaths among four cohorts of coal miners was made (*101*). Forty cases were identified among 6066 deaths in a total cohort of approximately 19,000 coal miners; age-at-death matched (4 to 1) comparison deaths were chosen from the same cohort. Exposure to electromagnetic fields was inferred on the basis of work underground for more than 25 years. This questionable exposure surrogate, the different lengths of follow-up for the cohorts, and the small number of cases are some of the weaknesses associated with this exploratory study. The authors found an overall odds ratio for leukemia of 2.53 and acknowledge the potential role played by other occupational exposures. Cigarette smoking histories and the frequency of coal miner's pneumoconiosis were comparable between groups. The data for one analysis (Table 2) are for all leukemias and subsets selected for comparison with those cell-types reported by other investigators. Gilman et al. (*101*) found an odds ratio of 8.22 ($p < 0.05$ level, 95% confidence bounds of 1.12 and 60.42) for chronic lymphocytic leukemia at this site.

Proportional Mortality Studies. One aspect of the controversy surrounding electromagnetic fields is derived from a series of studies conducted with population-based data. These reports represent many different geographical areas. The studies were conducted with an analytical calculation called the proportional mortality ratio (PMR), a method with known limitations (*102–104*). Case and comparison data, including the exposure information, are taken from death certificates. The basis of analysis is the proportion of deaths within certain groups (i.e., occupation titles) that result from a certain cause. These investigations were designed to generate hypotheses; however, their convenience makes them useful for testing the consistency of an association across different exposed groups and geographic locations (*13, 105*).

The first of these studies to link occupations with presumed electromagnetic field exposures came from a death certificate study in Washington State (*106*). Proportional mortality ratios in the range of 1.4 to 1.6 were cited for leukemia in males 20 years of age and older. A PMR-type study from California reported a similar finding using cancer incidence data. This report examined subgroups of leukemia cell types from the cases (white males) diagnosed from 1972 to 1979. The risk estimates from the "all-jobs" category were from 1.3 to 2.1. Acute myelogenous leukemia was suggested as having the greatest association with electrical occupations (*107*).

A British study, using leukemia incidence data for white males 15 to 74 years old (1961–1979), reported risk estimates of about 1.2 for all leukemias and acute

myelogenous leukemia (*108*). A study of leukemia deaths in England and Wales, from 1970 to 1972 (males, 15–74 years old), gave PMR values for various electrical occupations of between 1.2 and 2.3 for leukemia and myeloid subgroups (*109*). In a companion study, the 1973 certificates for male leukemia deaths over 15 years of age were matched by age, sex, and year of death to noncancer death certificates. Again, electrical occupations were found to be associated with the leukemia deaths, with a statistically significant odds ratio of 2.1 (*109*). Another British PMR-type study on ocular cancer reported an elevated occurrence among electrical occupations. A risk estimate of 2.4 is calculated from the data (*110*).

The National Institute for Occupational Safety and Health (NIOSH) (*111*) conducted an investigation of cancer mortality at an electronics manufacturing plant in Wisconsin. Deaths among approximately 99% of the company's employees were ascertained for the period from 1950 to 1980. This study reported a PMR for brain cancer (both sexes, all salary groups) of 1.95. A case-comparison analysis was performed with matched subjects (4 to 1) from the same company. The analysis focused on specific job categories; however, because of the small number, only three groups could be analyzed (machine operators, maintenance workers, and office workers). For these groups, the respective odds ratios were 1.4, 3.0, and 3.0; the description in Table 2 is for the machine operators category (*111*). Brain cancer was studied in Maryland men (20 years and older) for the years 1969 to 1982 (*112*). A PMR of 2.78 was cited for occupations thought to have high electrical field exposure. Lin et al. (*112*) used a case-comparison design to further test this possible association and cited an odds ratio of 2.15 for brain cancer and electrical occupations.

Recently, Milham (*113*) reported on leukemia mortality among members of a group of amateur radio operators in Washington State and California. Male deaths from 1971 to 1983 were identified via the group's monthly newsletter; these were compared with mortality data for each state during the same time period. The PMR for all leukemias was 1.9, with PMRs for myeloid cell types ranging from 2.5 to 2.9 (*113*).

Pearce et al. (*114*) also report the findings for a case-comparison study performed in New Zealand. In this study, leukemia cases were matched to four other cancer cases in the National Cancer Registry. Occupations having presumed electric and magnetic field exposure were the criteria investigated. Electromagnetic field occupations gave an overall odds ratio of 1.7, with some subcategories indicating no increased risk and others having odds ratios from 3.9 to 8.1 (*114*).

A PRM study using 1963 to 1978 mortality data (white males, 20 years of age and older) from the state of Wisconsin was reported recently (*115*). Electrical occupations were analyzed to assess the risk of leukemia and acute leukemia; the PMRs based on all electrical occupations were 1.03 and 1.13, respectively. Most of the occupation-specific PMRs were less than 1.0, and the patterns observed by Milham (*106*) and Wright et al. (*107*) were not observed in the Wisconsin findings. Elevated PMRs were reported for both electrical engineers (Table 2) and radio and telegraph operators (PMR = 2.35 and 3.0 for leukemia and acute leukemia, respectively) (*115*).

Other Reports. A review of five rare pediatric cancers in Florida included several environmental factors that may have been common to the cases. Residential proximity to electrical power lines was one of those factors. The close aggregation of the cases in space and time had drawn the interest of the investigators. Residential proximity to power lines was not a hypothesis of the study (*116*). Preliminary results from a Colorado study suggest an association between the use of electric blankets and infertility and birth defects. Relatively strong electromagnetic fields may be generated by electric blankets under certain circumstances, according to the authors. The seasonal variation of rates of births and birth defects may agree with the time periods of peak electric blanket use (*117*). Workers in 400 kV electrical substations have been studied for chromosomal effects in circulating lymphocytes. This study of 38 workers (19 exposed and 19 comparison employees) was conducted in Sweden (*118*). Exposed workers were found to have elevated rates of chromosomal aberrations (breaks) and micronuclei, but no elevation in sister chromatid exchanges. The effects were postulated as the result of exposure to transient electrical currents (spark discharges) (*118*).

Two British studies have recently been completed, but their results are not yet finalized. Preliminary findings were presented at an international conference. A study was conducted of leukemia cases from 1965 to 1980 in four south London communities (*119*). Case and comparison data (i.e., persons with solid tumors) were taken from the Thames Cancer Registry. Despite 769 cases and 1436 comparison subjects being studied, small numbers of subjects actually lived near high-voltage electric power lines (in England power lines are predominantly underground). This study found evidence of an elevated risk (odds ratio of 1.9) for those living less than 50 m from overhead lines; however, there was no evidence presented for those living within 100 m of the lines (*119*).

Another case-comparison study considered pediatric brain cancers, neuroblastomas, and leukemias from 1970 to 1979 in the Yorkshire area (*120*). Magnetic field exposure levels were calculated from the maximum current load on overhead power lines between 1974 and 1984. Actual measurements were made in 44 homes that were not a part of the study. The range for calculated magnetic fields was 0.002 to 16.8 mG, with a median of 0.09 mG; median kitchen levels were only slightly greater than in other locations in the homes (despite electrical appliances operating in some instances). None of the analyses from this study indicated an elevated risk of childhood cancer as a result of magnetic fields from overhead power lines (*120*).

Currently, there are at least six epidemiologic studies in progress. Two are industry-based cohort studies in

England and Sweden (*121,122*). These studies are relatively small (1000 and 56 workers, respectively), yet they involve close clinical follow-up and can provide data on common health events and acute phenomena. Two large retrospective studies are under way in Denver and Seattle as a part of the research on electromagnetic fields by New York State. These investigations are studying childhood (425 cases) and adult leukemia (160 cases) in Colorado and Washington, respectively. The studies include measurements of electric and magnetic fields within the subjects' homes and may thereby shed some light on the exposure-response relationship (*123,124*).

In Washington State, a study of a possible association between breast cancer and electromagnetic fields/light-dark cycles is being initiated (*125*). This proposed study of human breast cancer is based in principle on findings from animal experiments linking exposure to electromagnetic fields or light to a reduction in melatonin levels; reduced melatonin levels have significantly increased dimethylbenz[a]anthracene mammary carcinogenesis (*38,125*). Finally, a case-comparison study of acute myeloid leukemia will be conducted on telephone employees from across the United States. About 160 cases and controls will be identified and investigated for occupational characteristics between the years of 1975 and 1980 (*126*). Each of the six studies described in the preceding paragraphs should have excellent statistical power for detecting small differences between comparison groups. The challenge before these investigators is to achieve the maximum validity possible by identifying and characterizing ELF field exposure.

Discussion

Some of the evidence from *in vitro* studies suggests possible ELF field effects on subcellular sites that result in increased growth rates. Some whole-animal data offer suggestions that some biologic systems may be perturbed (e.g., neurologic or neuromuscular enhancement and developmental effects). Most of these laboratory studies have in common good exposure characterization, especially when compared with human studies. These studies, however, also have weak statistical power because of low-level effects (e.g., doubling) and/or small sample sizes used in the experiments. Suggestions have been made that ELF fields may act as promoters of carcinogenesis. An epidemiologic study designed to detect promotion has not yet been conducted, and the appropriate study design would require some development. The exposure measurement technology for the necessary research is just now coming into existence. And even as the technology is developing, there are questions about how to use it. Human exposures to ELF fields include perplexing patterns of electric and magnetic fields and numerous (uncharacterized) confounding exposures to other agents (e.g., combustion by-products, cigarette smoke, radon, etc.).

As with all basic research, the necessary ELF field experiments with animals and lower life forms must be conducted with vigorous control of exposure variables. This control includes constant exposure to a fixed intensity of ELF fields, with no other potentially confounding exposure. Yet, this exposure precision is not at all similar to the human experience that entails a very complex set of exposure conditions (*105*). Most of the risk estimates in Table 2 are less than 3.0. The larger risk estimates in the table or from published studies are each based on small sample sizes and have wide confidence bounds, irrespective of statistical significance. To emphasize this point, we have calculated a summary risk estimate for leukemia with the Mantel-Haenszel method using four of the case-comparison studies (*91,92,109,114*). This summary odds ratio is 1.69, chi-square = 17.535 ($p < 0.01$, 95% confidence bounds of 1.32 to 2.16) (*127*).

Risks take on public health significance not only because of the nature of the hazard but also because of the size of the population at risk. A reasonable amount of data has been gathered to support the hypothesis that electric fields in and of themselves are not carcinogenic. However, essentially everyone is exposed. Exposures occur not only when passing under electrical power lines but also at work or in our residence (*18,128,129*). Based on a qualitative synthesis of the available research on ELF fields, the risk for serious health events is probably small and involves a very complex set of exposure conditions. It is not at all evident how one would extrapolate the ELF experimental data to arrive at estimates of human health risk. If the laboratory exposure conditions were designed to be more similar (e.g., complex) to human exposures, the benefit would be substantially fewer, qualifying assumptions when translating effects (or their absence) in animal systems to human populations (*105*). Vigorous experiments of this type, however, would require a substantial funding commitment.

There are many nuances to be considered with the pattern of ELF field exposures: What is the source of the exposures? What is the intensity and frequency (Hz) of the exposure(s)? How long is a person exposed, and what is the time schedule for the exposure? What other factors may be relevant to the person's risk for the health event of interest? These questions are compounded by our lack of knowledge about the fundamental mechanism(s) relating to the observed bioeffects. Assuming all these questions could be answered, there is also the matter of regulating the exposure and the cost of that regulation. With a residential exposure, how will basic rights issues be resolved? Will warning labels be the approach for alerting the public to a hazard that it may want to accept? Will industrial standards be changed, as with automobile emissions?

Conclusions

The experimental data presented here would indicate that if there are health effects associated with exposure to ELF fields, these are likely to involve a complex exposure pattern of intensities, durations, and frequen-

cies that has yet to be ferreted out. If these findings should persist, such a complicated exposure-response scenario could have significant implications to human health risk assessment efforts. Specifically, how can it be done?

If a risk of human cancer should exist, it is likely to be very small, perhaps on the order of 2.0 or less, and then only for highly specific groups in the population. This small risk represents a methodological obstacle for epidemiologic research with regard to sample size considerations. This is particularly true since confounding exposures will almost certainly have to be taken into account if a carcinogenic effect is to be studied. The necessity for *in vitro* studies to seek possible mechanisms of carcinogenic action by ELF fields is patent. Additionally, there is the persistent question regarding what aspect of exposure should be studied and how to best assess its effect. Excellent research efforts are in progress to address these research questions and to develop techniques for measuring ELF exposure.

A final salient question remains in regard to the public's health and a philosophical quandary over "when is enough enough." What is the relative priority for further ELF fields research? In light of the ubiquity of ELF fields, the (apparently) socially desirable sources of exposure, the low level risk at issue, the uncertainty over the role of other (confounding) exposures, and doubts over how to regulate exposure if evidence of a health risk should be found, are we going to look closer to see if there is any real health effect? Appropriate studies may prove very costly.

Research sponsored by the Martin Marietta Energy Systems, Inc., under Contract No. DE-AC05-840R21400 with the U.S. Department of Energy. The literature review for this paper is complete through 1985; a few later references were added only to meet reviewers' comments.

REFERENCES

1. Editor. 35th Annual electric utility industrial forecast. Electrical World (September 1984): 49–56.
2. Dodge, C. H. High voltage line and extremely low frequency communications systems: Health and safety concerns. Congressional Research Service. The Library of Congress, Washington, DC, 1984.
3. Sheppard, A. R., and Eisenbud, M. Biological Effects of Electric and Magnetic Fields of Extremely Low Frequency. New York University Press, New York, 1977.
4. Becker, R. O., and Marino, A. A. Electromagnetism and Life. Pub. State University of New York, New York Press, New York.
5. Asanova, T. P., and Rakov, A. M. Health conditions of workers exposed to electrical fields on open switchboard installations of 400–500 kV: Preliminary report. Gig. Tr. Prof. Zabol. 10: 50–52 (1966) (Russian).
6. Sazanova, T. E. Physiological and hygienic assessment of the working conditions at the outdoor switchyard 400 and 500 kV. Proceedings of the Institute of Labor Protection Under the All-Union Central Council of Trade Unions 1967; 63: USSR (Russian). Available with translation by G. Knickerbocker in IEEE Power Engineering Society Special Report No. 10., Piscataway, NJ.
7. World Health Organization. Environmental Health Criteria: Extremely Low Frequency ELF Electrical and Magnetic Fields (up to 300 Hz) with Particular Reference to Power Frequencies (50/60 Hz). Environmental Health Division, WHO, Geneva, 1984.
8. Knave, B. Epidemiological studies on effects of exposure to ELF electromagnetic fields. Proceedings of the NATO Conference on Bioeffects and Dosimetry of ELF Electrical Fields. (Grandolopho, Michaelson, and Rende, Eds.), Plenum Press, New York, 1984.
9. Fole, F. F., and Dutrus, E. New contribution to studies of electromagnetic fields generated by high voltages. Med. Y. Eeq. del Trab. 1974: 22(87): 25–44 (Spanish).
10. Roberge, P. F. Study on the state of health of electrical maintenance workers on Hydro-Quebec 735 kV power transmission system. Final report (French) Hydro-Quebec, Quebec, Canada, 1976.
11. Easterly, C. E. Cancer link to magnetic fields exposure: A hypothesis. Am. J. Epidemiol. 114(2): 169–173 (1981).
12. Medical Study Group. Effects of electromagnetic fields associated with electricity production and distribution: an assessment of the present knowledge. Presented at the Brussels Congress of the International Union of Producers and Distributors of Electrical Energy, Brussels, Belgium, 1982.
13. Electromagnetism and cancer (editorial). Lancet i: 224 (1983).
14. Douglas, J. Electromagnetic fields and human health. Elect. Power Res. Inst. J. 9(4): 14–21 (1984).
15. Morgan, M. G., Florig, H. K., Nair, I., and Lincoln, D. Powerline fields and human health. Spectrum 1985; 2: 62–68.
16. Kaune, W. T., and Phillips, R. D. Comparisons of the Coupling of Grounded Humans, Swine, and Rats to Vertical, 60-Hz Electric Fields. Bioelectromagnetics 1(2): 117–129 (1980).
17. Chartier, V. L. Occupational health study of electrical workers (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
18. Barnes, F. S., Wachtel, H., and Savitz, D. Measurements of the distribution of 60-Hz fields in residences (abstract). Presented at the Bioelectromagnetics Society Meeting. San Francisco, 1985.
19. Bracken, T. D. Comparison of electric field exposure monitoring instrumentation. Electric Power Research Institute, Research Project 799-19. Electric Power Research Institute Pub. EA-4085. Palo Alto, CA, 1985.
20. Sheppard, A. R. Biologic effects of high voltage AC transmission lines—with reference to the Colstrip Project Garrison—Spokane HVTL. Prepared for the Montana Dept. of Natural Resources and Conservation, Helena, Montana. National Tech. Info. Ser. Pub. P383-207241, U.S. Dept. Commerce. Springfield, VA, 1983.
21. Going, M. C. 1984 Annual statistical report. Electrical World (April 1984): 49–72.
22. Phillips, R. D., Gillis, M. F., Kaune, W. I., and Mahlum, D. D. Biologic effects of extremely low frequency electromagnetic fields. Tech. Info. Center, U.S. Dept. Energy, Oak Ridge, TN, 1979.
23. National Bureau of Standards. Electrical parameters in 60 Hz biological exposure systems and their measurement: A primer. NBS Technical Note 1191. U.S. Dept. Commerce, Washington, DC, 1984.
24. Fraiser, M. E. In vitro effects of electrical fields. Pacific Northwest Laboratory Annual Report for 1981. Submitted to the U.S. Department of Energy, Office of Energy Research. PNA-4100 1982, Part 1: 39–41.
25. Williams, G. L. Genetic effects of electric fields (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. of Health. St. Louis, MO, 1982.
26. Kamin, G., and Adey, W. R. Tests of the modification of electrolyte conductivity and ionic concentration near a boundary layer due to an external RF electric field (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
27. Sheppard, A. R., Burton-Sagan, M., and Adey, W. R. Comparative study of modulation of aplasia pacemaker neuron firing

rates by extracellular fields or injected currents (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
28. Bawin, S. M., Abu-Assal, M., Mahoney, M. D., Sheppard, A. R., and Adey, W. R. Effects of ELF fields on penicillin treated rat hippocampal slices (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
29. Blackman, C. F., Benane, S. G. Effects of ELF (1–120 Hz) and modulated (50 Hz) RF fields on the efflux of calcium ions from brain tissue in vitro. Bioelectromagnetics 6: 1–11 (1985).
30. Delgato, J. M. R., Leal, J., Monteagudo, J. L., and Garcia, M. G. Embryological changes induced by weak extremely low frequency electromagnetic fields. J. Anat. 134(3): 533–551 (1982).
31. McClanahan, B. J., and Phillips, R. D. The influence of electric field exposure on bone growth and fracture repair in rats. Bioelectromagnetics 4(1): 11–21 (1983).
32. Gunderson, R., Greenbaum, B., and Goodman, E. Effects of 60 Hz electromagnetic fields on calcium efflux and neurotransmitter release (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
33. Winters, W. D., and Phillips, J. L. Electromagnetic field induced bioeffects in human cells in vitro (abstract). 23rd Hanford Life Sciences Symposium. Interaction of Biological Systems With Static and ELF Electric and Magnetic Fields. Richland, WA, 1984.
34. Liboff, A. R., Williams, T., Strong, D. M., and Wister, R. Time varying magnetic fields: Effect on DNA synthesis. Science 223: 818–819 (1984).
35. Livingston, G. K. The reproductive integrity of mammalian cells exposed to 60 Hz electromagnetic fields (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
36. Gona, A. G., and Yu, M. C. Effects of 60 Hz electric and magnetic fields on the developing rat brain (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
37. Lin-liu, S., Cain, C., and Adey, W. R. Effects of ELF fields on forskolin-induced cAMP accumulation in hippocampal slices (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
38. Anderson, L. E. Neurochemical effects of 60 Hz electric fields (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
39. Vasquez, B. J., McNeeley, P., and Adey, W. R. Neurochemical correlates of EMF exposure (abstract). Contractors Review Meeting. U. S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
40. Frazier, M. E., Samuel, J. E., and Koune, W. T. Viabilities and mutation frequencies of CHO-K1 cells following exposure to 60 Hz electric fields (abstract). 23rd Hanford Life Sciences Symposium. Interaction of Biological Systems with Static and ELF Electric and Magnetic Fields, Richland, WA, 1984.
41. Noda, M., Johnson, D., Chiabrera, A., and Rodan, G. A. The effect of 60 Hz electric and magnetic fields on the growth of osteoblastic osteosarcoma cells in culture (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
42. Cain, C. D., Luben, R. A., and Adey, W. R. Pulsed electromagnetic field effects on PTH stimulated cAMP accumulation on desorption in mouse calvariae (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
43. d'Ambrusio, G., Scaglione, A., DiBerardino, D., Lioi, M. B., Iannuzzi, L., Mostacciuolo, E., and Scorfi, M. R. Chromosomal aberrations induced by ELF electrical fields. J. Bioelectricity 4(1): 279–284 (1985).
44. Cohen, M. M., Kunska, A., McCulloch, D., and Harrison, G. H. Cytogenic effects of electromagnetic fields on human lymphoid cells (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
45. Byus, C. V., and Adey, W. R. Alterations in protein kinase activity following exposure of cultured human lymphocytes to modulated microwave fields (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
46. Adey, W. R. Cell membranes, the electromagnetic environment and cancer promotion. Contractors Review Meeting, U.S. Department of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. of Health. Denver, CO, 1986.
47. Lyle, D. B., Kami, G. W., and Adey, W. R. T-Cell growth factor responsiveness/production and H^3 thymidine incorporated by myeloid leukemia cells in the presence of a 60 Hz pulsed, 20 gauss magnetic field and/or 12-o-tetradecanoylphorbol-a-acetate (TPA) (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
48. Winters, W. D., and Phillips, J. L. The search for cells sensitive to electromagnetic fields (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
49. Fam, W. Z. Long-term biological effects of a very intense 60 Hz electrical field on mice. IEEE Trans. Biomed. Eng. 27(7): 376–381 (1980).
50. Sikov, M. R., Montgomery, L. D., and Smith, L. G. Developmental toxicology studies with 60-Hz electric fields. Interim Report, Battelle Memorial Institute, Pacific Northwest Laboratory. U.S. Dept. of Energy. Division of Electrical Energy Systems. DOE/RL/01830-TV, 487–502 (1981).
51. Sikov, M. R., Montgomery, L. D., Smith, L. G., and Phillips, R. D. Studies on prenatal and postnatal development in rats exposed to 60 Hz electric fields. Bioelectromagnetics 5(1): 101–112 (1984A).
52. McClanahan, B. J. Evaluation of the mutagenic potential of 60 Hz electric fields on germ cells of male mice (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
53. Ossenkopp, K. P., and Cain, D. P. Effects of 60 Hz magnetic fields on metrazol induced seizures in rats and morphine analygesia levels in mice (abstract) Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
54. Carsten, A. L., Baum, J., Benz, R. D., and Kuehner, A. Reproductive, dominant lethal mutation and cytogenic studies in 60 Hz, 50 kV/m, and 60 gauss magnetic fields (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
55. Morris, J. E. Immunological studies and 60 Hz electrical fields (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
56. Ehret, C. F. An analysis of how and why 60 Hz electric fields cause circadian phase shifts and dyschronism in small rodents (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
57. Marino, A. A., Becker, R. O., and Ullrich, B. The effect of continuous exposure to low frequency electric fields on three generations of mice: A pilot study. Experientia 32: 565–566 (1976).
58. Marino, A. A., Berger, T. J., Austin, B. P., Becker, R. O., and Hart, F. X. In vivo bioelectrochemical changes associated with

exposure to extremely low frequency electric fields. Physiol. Chem. Phys. 9: 433–441 (1977).
59. Marino, A. A., Reichmanis, M., Becker, R. O., Ullrich, B., and Cullen, J. M. Power frequency electric field induces biological changes in successive generations of mice. Experientia 36: 309–311 (1980).
60. Easterly, C. E., Aldrich, T. E., and Morris, M. D. Dipolar nature of ELF bioeffects: Inclusion of negative data in a structured argument (abstract). 23rd Hanford Life Sciences Symposium. Interaction of Biological Systems with Static and ELF Electric and Magnetic Fields, Richland, WA, 1984a.
61. Hilton, D. L., Phillips, E. D. Growth and metabolism of rodents exposed to 60-Hz electric fields. Bioelectromagnetics 2(4): 381–390 (1981).
62. Free, M. J., Kaune, W. T., Phillips, R. D., and Cheng, H. Endocrinological effects of strong 60-Hz electric fields on rats. Bioelectromagnetics 2(2): 105–122 (1981).
63. Lovely, R. H. Studies of the behavioral toxicity of 60 Hz electric fields (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
64. Anderson, L. E., Rommereim, D. N., Kaune, W. T., and Sikov, M. R. Multiple-dose teratologic evaluation. Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. Washington, DC, 1985.
65. Michaelson, S. M., and Quinlan, W. J. Neuroendocrine regulation in rats exposed to 60 Hz electric fields (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
66. Salzinger, K., Birenbaum, L., Cole, G., Freimark, S., McCullough, M., and Phillips, D. The effect of ELF fields on the behavior of rats (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
67. Stern, S., Laties, V. G. 60 Hz electric fields: Detection by female rats. Bioelectromagnetics 6(1): 99–103 (1985).
68. Rommereim, D. N., Kaune, W. T., and Buschbom, R. L. Reproduction and development of rats chronically exposed to 60 Hz electric fields (abstract). 23rd Hanford Life Sciences Symposium. Interaction of Biological Systems with Static and ELF Electric and Magnetic Fields, Richland, WA, 1984.
69. Jaffee, L. F., and Stern, C. D. Strong electrical currents leave the primitive streak of chick embryos. Science 206: 569–571 (1979).
70. Jaffe, R. A., Laszewski, E. L., Carr, D. B., and Phillips, R. D. Chronic exposure to a 60-Hz electric field: Effects on synaptic transmission and peripheral nerve function in the past. Bioelectromagnetics 1: 131–147 (1980).
71. Carsten, A. L., Baum, J. W., Benz, R. D., and Kuehner, A. D. Dominant lethal mutation, reproduction and cytogenetic studies in 60 Hz, 50 kV/m – 10 Gauss magnetic fields. Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Line Projects. N.Y. Dept. Health. Washington, DC, 1985.
72. Greenberg, B., Bindokas, V., and Gauger, J. R. Biological effects of 765-kV transmission line: Exposures and thresholds in honeybee colonies. Bioelectromagnetics 2: 315–328 (1981).
73. Greenberg, B., Bindokas, V., and Gauger, J. R. Honey bees and EHV transmission lines: Mechanism of biological effects (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
74. Hansson, H. A., Darnfors, C., Rozell, B., and Stemme, S. Effects of experimental exposure of power-frequency electromagnetic fields on the nervous system (abstract). 23rd Hanford Life Sciences Symposium. Interaction of Biological Systems with Static and ELF Electric and Magnetic Fields, Richland, WA, 1984.
75. Sikov, M. R., Buschbom, R. L., and Kaune, W. T. Evaluation of reproduction and development in Hanford miniature swine exposed to 60 Hz electric fields (abstract). 23rd Hanford Life Sciences Symposium. Interaction of Biological Systems With Static and ELF Electric and Magnetic Fields. Richland, WA, 1984.
76. Lee, J. M. Environmental studies of AC and DC transmission lines (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
77. Miller, M. W., Inoue, I., and Carstensen, E. L. Biophysical aspects of electric fields effects at the cellular level (abstract). 23rd Hanford Life Sciences Symposium, Interaction of Biological Systems with Static and ELF Electric and Magnetic Fields, Richland, WA, 1984.
78. Inoue, M., Miller, M. W., Cox, C., and Carstensen, E. L. Growth rate and mitstic index analysis of *vicia faba L.* roots exposed to 60 Hz electric fields. Bioelectromagnetics 6: 293–303 (1985).
79. Sanders, D. E., Sanders, J. A., and Sangenaris, J. Low milk production associated with transient environmental voltage. J. Am. Vet. Med. Assoc. 179(1): 69 (1981).
80. Kirk, J. H., Reese, N. D., and Bartlett, P. C. Stray voltage on Michigan dairy farms. J. Am. Vet. Med. Assoc. 184(4): 426–428 (1984).
81. Wolpaw, J. R., Seegal, R. F., and Dowman, R. Chronic effects of 60 Hz electric and magnetic fields on primate central nervous system function (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
82. Sulzman, F. M., Murrish, D. E., and Sickles, S. A. Effects of electromagnetic fields on primate circadian rhythms (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
83. Lotz, W. G., and Saxon, J. L. Growth and sexual maturation of rhesus monkeys chronically exposed to ELF electrical and magnetic fields (abstract). 23rd Hanford Life Sciences Symposium. Interaction of Biological Systems with Static and ELF Electric and Magnetic Fields, Richland, WA, 1984.
84. Rogers, W. R., Lucus, J. H., and Orr, J. L. High intensity 60 Hz electric field exposure facility for nonhuman primates (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
85. Stollery, B. T. Human exposure to 50 Hz electrical currents (abstract). 23rd Hanford Life Sciences Symposium. Interaction of Biological Systems with Static and ELF Electric and Magnetic Fields, Richland, WA, 1984.
86. Fotopoulos, S. S., Cook, M. R., Gerovich, M. M., Koontz, E., Graham, C., and Cohen, H. D. Effects of 60 Hz fields on human biochemical activity (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
87. Graham, C., Cohen, H. D., Cook, M. R., Gerkovich, M. M., Phelps, J. W., and Fotopoulos, S. S. Human exposure to 60 Hz fields: effects on performance, physiology, and subjective state (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
88. Utidjian, H. M. D. Feasibility of an epidemiological study of workers occupationally exposed to high voltage electrical fields in the electrical power industry. Prepared by Equitable Environmental Health, Inc., Rockville, MD, for the Electrical Power Research Institute. Palo Alto, CA, 1979.
89. Knave, B., Gamberale, F., and Bergstrom, S. Long-term exposure to electrical fields. A cross-sectional epidemiological investigation on occupationally exposed high voltage substation workers. Scand. J. Work Environ. Health 5: 115–125 (1979).
90. Stopps, G. J., Janischewsky, W. Epidemiological study of workers maintaining HV equipment and transmission lines in Ontario. Canadian Electrical Assoc. Research Report, 1979.
91. Wertheimer, N., and Leeper, E. Electrical wiring configurations and childhood cancer. Am. J. Epidemiol. 109: 273–284 (1979).
92. Fulton, J. P., Cobb, S., and Preble, L. Electrical wiring config-

uration and childhood leukemia in Rhode Island. Am. J. Epidemiol. 111: 292–296 (1980).
93. Wertheimer, N., and Leeper, E. Electrical wiring configurations and childhood cancer in Rhode Island. Am. J. Epidemiol. 112: 461–462 (1980).
94. Tomenius, L., Hellstrom, L., and Enander, B. Electrical constructions and 50 Hz magnetic field at the dwellings of tumor cases (0–18 years of age) in the county of Stockholm (abstract). Int. Symp. Occup. Health and Safety Mining and Tunnelling, Prague, 1982.
95. Wertheimer, N., and Leeper, E. Adult cancer related to electrical wires near the home. Int. J. Epidemiol. 11(4): 345–355 (1982).
96. Reichmanis, M., Perry, F. S., Marino, A. A., and Becker, R. O. Relationship between suicide and the electrical field of overhead power lines. Physiol. Chem. Phys. 11: 395–404 (1979).
97. Perry, F. S., Reichmanis, M., Marion, A. A., and Becker, R. O. Environmental power-frequency magnetic fields and suicide. Health Phys. 41: 267–276 (1981).
98. Nordstrom, S., Birke, S., and Gustavson, L. Reproductive hazards among workers at high voltage substations. Bioelectromagnetics 4: 91–101 (1983).
99. Vagero, D., and Olin, R. Incidence of cancer in the electronics industry: using the new Swedish Environmental Registry as a screening instrument. Br. J. Ind. Med. 40: 188–192 (1983).
100. Spitz, M. R., and Johnson, C. C. Neuroblastoma and paternal occupation. Am. J. Epidemiol. 121: 924–929 (1985).
101. Gilman, P. A., Ames, R. G., and McCawley, M. A. Leukemia risk among U.S. white male coal miners. J. Occup. Med. 27(9): 669–671 (1985).
102. Milham, S. Methods in occupational mortality studies. J. Occup. Med. 17(9): 581–585 (1975).
103. Kupper, L. L., McMichael, A. J., and Symons, M. J. On the utility of proportional mortality analysis. J. Chronic Dis. 31: 15–22 (1978).
104. Decoufle, P., Thomas, T. L., and Pickle, L. W. Comparison of the proportionate mortality ratio and standard mortality ratio risk measures. Am. J. Epidemiol. 111(3): 263–269 (1980).
105. Easterly, C. E., and Aldrich, T. E. Human health risk assessment needs help from ELF bioeffects researchers. Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
106. Milham, S. Mortality from leukemia in workers exposed to electrical and magnetic fields. N. Engl. J. Med. 307: 249 (1982).
107. Wright, W. E., Peters, J. M., and Mack, T. M. Leukemia in workers exposed to electrical and magnetic fields. Lancet ii: 1160–1161 (1982).
108. Coleman, M., Bell, J., and Skeet, R. Leukemia incidence in electrical workers. Lancet i: 982–983 (1983).
109. McDowall, M. E. Leukemia mortality in electrical workers in England and Wales. Lancet i: 246 (1983).
110. Swerdlow, A. J. Epidemiology of eye cancer in adults in England and Wales. 1962–77. Am. J. Epidemiol. 118: 294–300 (1983).
111. Delco Electronics Division, NIOSH. Health hazard evaluation report. Health Evaluations and Technical Assistance, 80-250-1529, 1984.
112. Lin, R. S., Dischinger, P. C., Conde, J., and Farrell, K. P. Electromagnetic fields exposure and the occurrence of brain tumors. J. Occup. Med. 27(6): 413–419 (1985).
113. Milham, S. Silent keys: Leukemia mortality in amateur radio operators. Lancet i: 812 (1985).
114. Pearce, N. E., Sheppard, R. A., Howard, J. K., Fraser, J., and Lilley, B. M. Leukemia in electrical workers in New Zealand. Lancet i: 811–812 (1985).
115. Calle, E. E., Savitz, D. A. Leukemia in occupational groups with presumed exposure to electrical and magnetic fields. N. Engl. J. Med. 313(23): 1477–1478 (1985).
116. Aldrich, T., Glorieux, A., and Castro, S. Florida cluster of five children with endodermal sinus tumors. Oncology 41(4): 233–238 (1984).
117. Wertheimer, N., and Leeper, E. Adverse effects on fetal development associated with sources of exposure to 60 Hz electric and magnetic fields (abstract). 23rd Hanford Life Sciences Symposium. Interaction of Biological Systems with Static and ELF Electric and Magnetic Fields, Richland, WA, 1984.
118. Nordenson, L., and Mild, K. H. Chromosomal aberrations in 400-kV substation workers (abstract). Presented at the Bioelectromagnetics Society Meeting, San Francisco, 1985.
119. Coleman, M., Bell, C. M., Taylor, H. L., and Thornton-Jones, H. Leukemia and electromagnetic fields: A case-comparison study. Proc. IEE International Conference in Medicine and Biology. IEE Conference Pub. 257. ISBN 0-85296320-3. Herts, England 122–125 (1985).
120. Myers, A., Cartwright, R. A., Bonnell, J. A., Male, J. C., and Cartwright, S. C. Overhead power lines and pediatric cancer. Proc. IEE International Conference in Medicine and Biology. IEE Conference Pub. 257. ISBN 0-85296320-3. Herts, England, 122–125 (1985).
121. Knave, B. Prospective investigation into the health risks associated with work on the generation and distribution of electrical power. Presented at Symposium 22-81 of the International Conference on Large High-Voltage Electric Systems, Paris, 1981.
122. Bonnel, J. A., and Norris, W. T. A U.K. program to study the response of people to 50-Hz electric and magnetic fields near an electric power plant (abstract). 23rd Hanford Life Sciences Symposium. Interaction of Biological Systems with Static and ELF Electric and Magnetic Fields, Richland, WA, 1984.
123. Savitz, D., Wachtel, H., and Barnes, F. Case control study of childhood cancer and electric and magnetic field exposures (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. Washington, DC, 1985.
124. Stevens, R. D. Electromagnetic fields and risk of leukemia (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. Washington, DC, 1985a.
125. Stevens, R. G. Epidemiological study of the risk of breast cancer and residential exposure to electromagnetic fields and light. Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. Washington, DC, 1985b.
126. Matanoski, G. M., and Obrams, G. I. Feasibility study to determine risk of leukemia in telephone linemen (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
127. Mantel, N., and Haenszel, W. Statistical aspects of the analysis of data from retrospective studies. J. Natl. Cancer Inst. 22(4): 719–748 (1959).
128. Vincent, W. R. Electric and magnetic fields in homes (abstract). Contractors Review Meeting. U.S. Dept. of Energy. Elect. Power Res. Inst. and N.Y. Power Lines Project. N.Y. Dept. Health. St. Louis, MO, 1984.
129. Wachtel, H., and Savitz, D. Residential electromagnetic propensity—conceptual basis and use in epidemiologic studies (abstract). 23rd Hanford Life Sciences Symposium. Interaction of Biological Systems with Static and ELF Electric and Magnetic Fields, Richland, WA, 1984.
130. Haenszel, W. D., Loveland, B., and Sirken, M. G. Lung cancer mortality as related to residence and smoking histories. 1. White males. J. Natl. Cancer Inst. 28: 1000–1001 (1962).
131. Schlesselmann, J. J. Case-Control Studies: Design, Conduct, Analysis. Oxford University Press, New York, 1982.
132. Beaumont, J. J., and Breslow, N. E. Power considerations in epidemiologic studies of vinyl chloride workers. Am. J. Epidemiol. 114: 725–734 (1981).
133. Miettinen, O. Estimability and estimation in case reference studies. Am. J. Epidemiol. 103: 226–235 (1976).