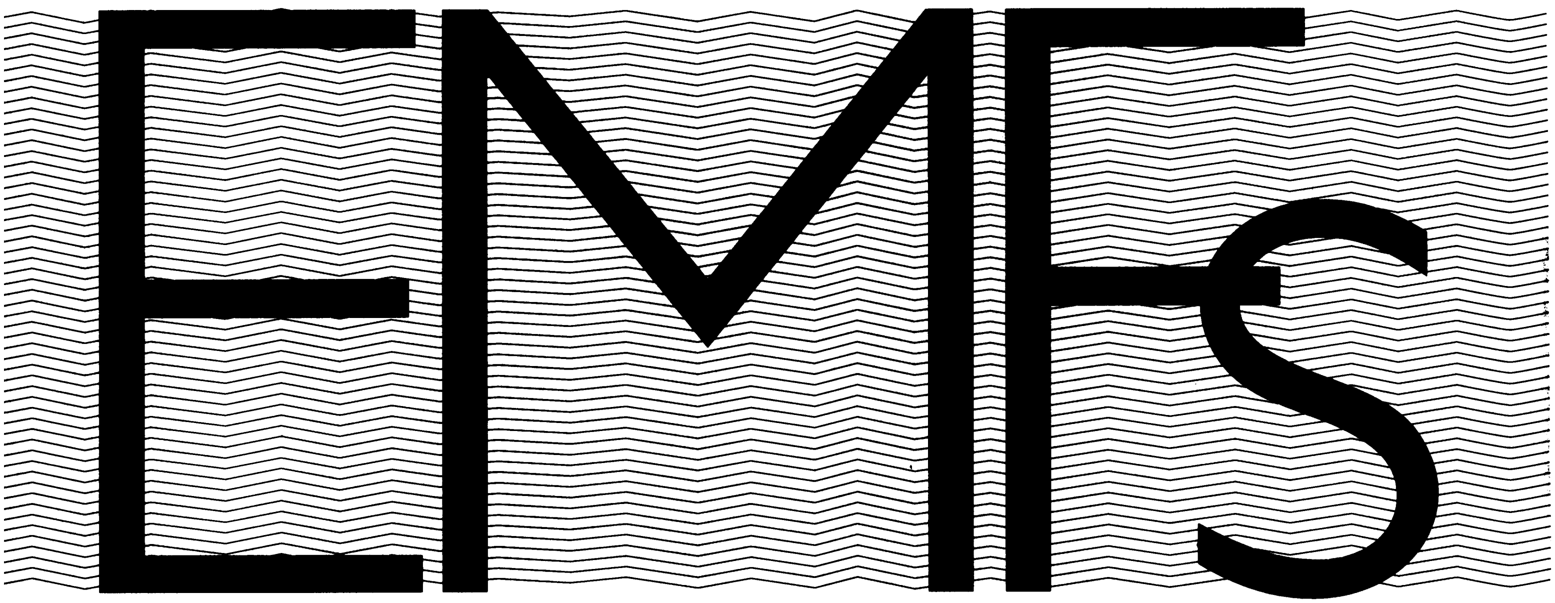

Cutting Through the Controversy

Daniel Wartenberg, PhD

SYNOPSIS

SOME SCIENTISTS ALLEGE that exposure to electric and magnetic fields generated by electric power delivery systems is responsible for certain cancers (particularly among children), reproductive dysfunction, birth defects, neurological disorders, and Alzheimer's disease. Some activist groups believe the hazard to be so great that they are calling for closure of schools and other public facilities near power lines and restructuring of the entire electric power delivery system. Some utilities, with equally strong beliefs, claim that there is no proof of risk. They argue that the science is insufficient to confirm the alleged associations and that no action is warranted.

This article provides a broad overview of the current scientific data on the association between magnetic fields and disease, providing summary risk estimates and highlighting the uncertainties in the data. Building on this information, three complementary policy perspectives are presented. From a fiscally conservative perspective, the cost of mitigation already instituted far exceeds the health protection offered and mitigation of other environmental risks is more important. From a cost-benefit view, only limited, low-cost mitigation should be considered. These measures, however, would substantially reduce many exposures. From an aggressive exposure reduction perspective, much can be done to reduce exposure by personal and societal actions. If the suggested association is validated, substantially reducing magnetic field exposure could lower health risks.

Many scientists and activists allege that EMFs, or electric and magnetic fields, cause health disorders ranging from cancer to Alzheimer's disease to reproductive problems. These allegations have given rise to a series of court cases and have been covered in countless news stories and TV specials. EMFs are even cited as causing decreases in property values. To some people, the EMF danger is a figment of the imagination of environmentalists, who once again are crying wolf over a concern for which there is virtually no scientific basis. To others, the data suggest a substantial hazard to which all of us are exposed, day in and day out. In communities across the country, concerns about EMFs have led to homes being sold, schools being closed, power lines being moved, and to controversies over the siting of facilities. Lack of consensus among the scientific community and limited firsthand understanding of the research on the part of lay people have enabled consumer fears in part to shape the policy debate.

In 1990, for example, Jersey Central Power and Light (JCP&L) proposed construction of a new, 10-mile segment of an electric power transmission line in Middletown, in response to increased residential development and electricity demand. When citizens learned of the proposed line, they organized, held informational meetings, and lobbied local politicians to block construction of the line. The controversy brewed for several months until JCP&L decided to shelve the planned line and make other arrangements to provide the required electricity.

In Texas, a school district sued a utility for siting a new 345 kilovolt (kV) electric power transmission line on school

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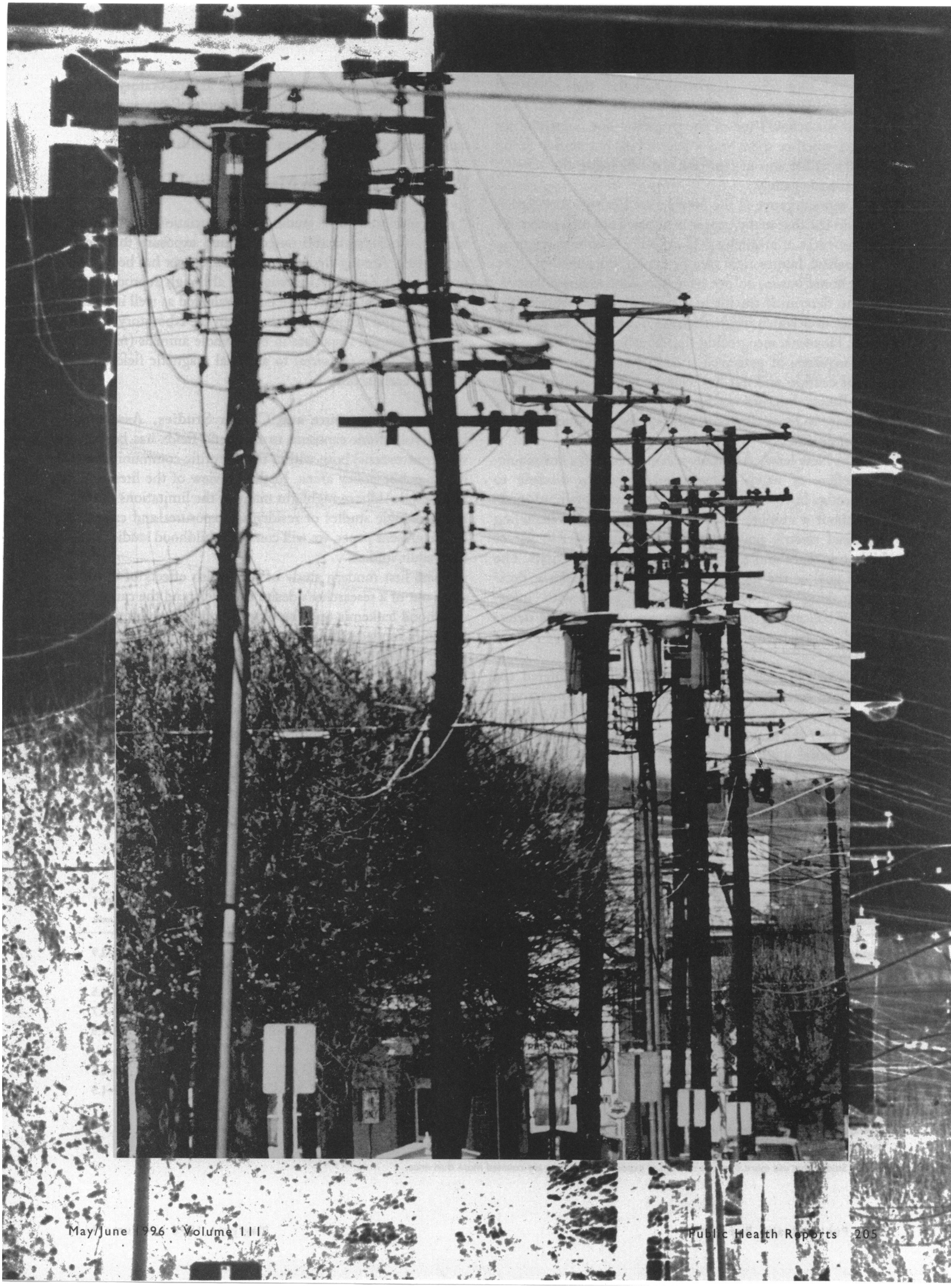

property.[1] The school district argued that the utility had abused its discretion in taking an easement and had disregarded the school's use of the property. The court did not rule on whether there was a health risk but simply found that the utility was at fault for not addressing the school's concerns adequately.[2]

A representative of the New Jersey Realtors Association has told me that many people concerned about the possible consequences of magnetic field exposure have been reluctant to purchase homes near electric power transmission lines. Most home buyers do not have adequate technical knowledge to determine the likely magnitude of exposure or the distance over which magnetic fields dissipate to background levels. However, recognizing that housing prices may fall as a consequence of perceived risk, they prefer to err on the side of caution and not buy near or within sight of power lines. Research results on the price of housing in relation to proximity to power lines are inconclusive, although they do suggest an effect.[3,4]

The New Jersey Assembly recently enacted a law requiring sellers of newly constructed homes to disclose to prospective buyers how and where they can obtain information about a number of potential local hazards, including overhead electric power transmission lines of 240 kV or higher voltages and electrical transformer substations. The stated goal of the legislation is to "facilitate prudent decision-making" by providing prospective buyers with "information concerning factors which can reasonably be determined to exist and which may affect the value of the residence."

Electric blanket manufacturers, too, have entered the fray. Until recently, an electric blanket's close contact with skin resulted in high magnetic field exposure (20 miligaus [mG]) over the many hours of use each night. Recognizing the potential marketing problems this might cause, engineers have redesigned the wiring within these devices to reduce the exposure by 95%.[5]

This article reviews epidemiologic and laboratory studies of the association of various measures of exposure with adverse health effects. The measurement of exposure is well understood; the effects of exposure on health less so.

Health Effects from Magnetic Field Exposures

Investigators have studied the association between a variety of adverse health outcomes and exposure to magnetic fields. Among the human studies, cancer has been the predominant outcome investigated, although reproductive and neurological effects have been evaluated as well in both residential and occupational studies. In the laboratory, studies have assessed responses in both whole animals (*in vivo*) and cell cultures (*in vitro*) to artificial magnetic fields. We consider each in turn.

Residential Exposure and Cancer Studies. Assessing health risks from exposure to magnetic fields has become very controversial both within the scientific community and in the public policy arena. In their review of the literature, Savitz and Ahlbom highlight many of the limitations of the epidemiologic studies of residential exposures and cancer.[6] In the present paper, we will consider childhood studies and then adult studies.

The first modern study of the health effects of EMFs arose out of a researcher's desire to understand the causes of childhood leukemia and the observation that children with leukemia tended to live closer to certain configurations of power lines.[7] The study compared the wire codings (see Sidebar "How Exposure is Assessed") in homes of children who died of cancer with the wire codings in homes of matched controls. The researchers, Wertheimer and Leeper, found that children who died of leukemia, lymphoma, or nervous system cancers were approximately two to three times more likely to have lived in homes with higher wire codings, (and hence, higher exposure) a statistically signifi-

Table 1. Summary of epidemiologic studies on EMF exposure and leukemia

Exposure activity	*Population studied*	*Exposure metric*	*Number of studies*	*Number reporting positive results*	*Number reporting statistically significant positive results ($P<0.05$)*	*Average risk[a] ratio*	*Range of risk ratios*
Residential	Children	Wire codes and distance	8	6	3	1.4[b]	1.0–2.9
		Spot measures	4	2	0	1.0	0.3–1.9
		Calculations	3	3	1	2.1[b]	1.5–2.5
	Adults	Wire codes and distance	5	5	1	1.4[b]	1.1–1.7
		Spot measures	3	3	0	1.3	1.2–1.9
		Calculations	1	1	0	1.4	—
Occupational	Adults	Job titles..................	33	23	6	1.2[b]	0.5–2.5
		Measurements	4	2	1	1.1	0.9–1.5

[a]Average risk ratio is defined as the weighted geometric mean of estimated odds ratios, where the weights are the inverses of the estimated variances.

[b]$P \leq 0.05$

NOTE: Studies that use more than one method of exposure assessment are counted more than once.

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cant association. This striking observation generated much interest among scientists and led to two avenues of research: studies focusing on residential exposures, as did Wertheimer and Leeper's study, and studies focusing on occupational exposures.

In the first subsequent residential study, Fulton and coworkers[8] attempted to replicate Wertheimer and Leeper's cancer results. While they found no difference between the home wire codings of children with leukemia and those without, subsequent review of their data revealed subtle but crucial problems. First, the researchers modified the wire coding system Wertheimer and Leeper had developed, which may have led to inaccuracies. Second, because the researchers assessed exposure at the birth address rather than the current address of children without cancer, they may have overestimated their exposures.[9]

In research conducted in Stockholm, Sweden, Tomenius advanced the study of childhood cancer and residential exposures by using direct, instantaneous (or "spot") measurement of magnetic fields in preference to wire codings.[10] He also categorized the generating source (transmission line, distribution line, transformer) and assessed the distance from the generating source to the subject's residence. This first use of directly measured exposures was an important step in attempting to refine the portion of the magnetic field exposure that is biologically relevant. His results surprisingly showed that magnetic field exposure was associated with a decreased risk of childhood leukemia but an increased risk of childhood brain tumors and lymphomas. Critics question the validity of Tomenius's study design: the use of single, instantaneous rather than long-term exposure measurements; the use of measurements taken at the residence doorstep; and his 200-meter cutoff point for distance effects, which may have inappropriately grouped many background exposures with high exposures.

In communities across the country, concerns about EMFs have led to homes being sold, and schools being closed.

Savitz and co-workers replicated Wertheimer and Leeper's study[7] in Denver, using more recent data and more extensive exposure assessment.[11] They used the same wire coding scheme as Wertheimer and Leeper and also conducted spot magnetic field measures in several rooms in each residence. This provided the first opportunity for a comparison of the wire coding and spot measurement approaches to exposure assessment. Their leukemia results

Table 2. Summary of epidemiologic studies on EMF exposure and brain cancers

Exposure activity	*Population studied*	*Exposure metric*	*Number of studies*	*Number reporting positive results*	*Number reporting statistically significant positive results (P<0.05)*	*Average risk[a] ratio*	*Range of risk ratios*
Residential	Children	Wire codes and distance	5	2	2	1.0	0.5–2.4
		Spot measures	4	3	1	1.1	0.7–3.9
		Calculations	3	1	0	1.3	0.7–2.3
	Adults	Wire codes and distance	1	1	0	1.1	—
		Spot measures	1	0	0	0.8	—
		Calculations	1	0	0	0.8	—
Occupational	Adults	Job titles..................	25	18	5	1.1	0.8–3.9
		Measurements	4	4	1	1.4	1.1–1.7

[a]Average risk ratio is defined as the weighted geometric mean of estimated odds ratios, where the weights are the inverses of the estimated variances.
[b]$P \leq 0.05$
NOTE: Studies that use more than one method of exposure assessment are counted more than once.

were qualitatively consistent with those reported by Wertheimer and Leeper irrespective of whether wire coding or spot measures were used, although the sizes of the relative risks were somewhat smaller and more likely attributable to chance. Results for brain cancers and lymphomas varied by the exposure metric, highlighting a disparity between the two exposure measures that still is under investigation. A partial explanation for the discrepancy is the small number of exposed cases (two) observed in each instance.

London and coworkers[12] conducted a case-control study of childhood leukemia in Los Angeles that was designed similarly to that of Savitz et al.[11] They also found that both wire codings and spot measures were positively associated with leukemia, although, in general, the associations were not statistically significant. In this study the relative risks were smaller for the analyses using spot measures.

Several studies followed, using similar methodologies and generating similar but not entirely consistent results.[13-18] Two other studies used similar exposure metrics (distance from power lines) but evaluated relative mortality rates in those living close to the power lines versus those living further away.[19,20] However, in these two studies effects on children were not separated from effects on older subjects.

The next major methodological advance was introduced in three Scandinavian studies in which historical exposures were calculated based on historical electricity-use data and wire configuration information.[21-23] All three found increased leukemia associated with higher exposures, although results for lymphomas and nervous system tumors varied by study.

In sum, there have been a total of 18 studies of childhood cancer and residential exposure to magnetic fields. Sixteen assessed leukemia risk, and several looked at lymphoma and nervous system risk. (See tables 1–3 for a summary of the results of the studies that provide adequate information for review.) While the study results are not entirely consistent, there is an unmistakable pattern to the results.[24-26] There is a preponderance of positive studies and of statistically significant positive results, more than one would expect by chance. When all studies are pooled, the average risks for leukemia, lymphoma, and nervous system tumors are all positive, with those for leukemia and nervous system tumors being statistically significant.[24] Further, these results are robust and are not sensitive to removal of any one individual study.[26] When stratified by exposure metric, all average risks are positive, but only leukemia risks assessed with wire codes, distance, and calculations are statistically significant.

A handful of studies of adult cancer and residential exposure to magnetic fields also have been conducted. The results of these studies show a less striking pattern, indicating a possible excess of leukemia but providing only limited information for lymphomas and brain cancers (tables 1–3).

There are several limitations to these epidemiology studies of residential exposure. First, no study was able to monitor each subject's exposure 24 hours a day from conception to diagnosis. In fact, it is not even known which aspect of exposure is most relevant: peak magnetic field strength, average magnetic field strength, variability of magnetic field strength, or others. One interesting disparity is that the results vary by the type of exposure metric used.[25,26] That is, for the leukemia studies, the wire coding, distance, and calculated exposure results produced stronger findings than those using spot measures. What is most surprising is that even though the means of measuring exposure improved in the more recent studies, the hypothesized association with cancer was not clarified as a result. This has led some to suggest that the true risk factor may be some more complex metric of magnetic fields. One caveat worth noting, however, is that each of the studies using spot measures failed to get measurements for even 50% of the study subjects, raising validity issues for any results—positive or null—using spot measurement data.

A second major limitation of the residential exposure studies is that there are many other potential explanations for elevated disease rates and only some have been investigated rigorously. The lack of improvement in the precision of the epidemiologic results as exposure measurement has improved has led some researchers to suggest that magnetic fields—or at least that aspect that we have been measuring—cannot be responsible for the disease. They posit that an alternative risk, which is correlated with proximity to power lines and hence wire codes, is the true risk factor and that magnetic fields are merely a confounder. While many potential confounders have been investigated (such as socioeconomic status, traffic density, appliance use, and pesticide use), to date none have shown a stronger association with the cancers than the wire codes. The possible presence of confounding is a limitation common to all epidemiologic studies.

A recent paper proposes an interactive effect between exposure to electric fields and airborne radon daughters as an explanation for the inconsistent leukemia data.[27] Arguing that the electrical fields from power lines caused increased deposition and subsequent skin absorption of the radon daughters, they suggest that the regions with both high electrical fields and high radon concentrations may impart

Basic Properties of Magnetic Fields

The principal health concerns related to electric power use, other than electrocution, are the effects of chronic exposure to magnetic fields. To appreciate the implications and limitations of exposure studies, it is helpful to understand a few basic principles of the physics of magnetic fields.

EMFs are the forces generated by the charge and flow of electrons. An electric field is created when a difference in electrical potential (voltage) is set up between two objects. These charged electrons seek to balance each other much in the way gravity seeks to balance an object that we lift up. When we release the object, it crashes to the floor. If we electrically connect two objects with a voltage difference, electrical current flows until there is no difference. In short, the imbalance creates a desire for balance. Movement toward that balance—the electrical current—generates what we call a magnetic field.

It is very important to understand the distinction between *electric fields*, which arise from a difference in electric potential or voltage, and *magnetic fields*, which arise from the flow of electricity or current. Unlike electric fields, which exist in the presence of energized (plugged in but not turned on) electrical wires or devices, magnetic fields are generated only when the electricity is put to use, when there is current flow. An electric light that is switched off generates an electric field. An electric light that is switched on generates both an electric and a magnetic field.

Interestingly, it is magnetic fields rather than electric fields that have been suggested as causes of adverse human health effects. Therefore most health effect studies have looked only at magnetic fields, not at electric fields.

Magnetic fields have a direction or polarity. A given magnetic field generated by electricity flow in one direction can be exactly balanced and canceled by an equal magnetic field flowing in the opposite direction at the exact same location. For example, the magnetic field arising from the flow of electricity from a wall outlet along a wire to a light bulb can be largely canceled by the magnetic field generated by the flow of electricity through the light bulb and back to the wall outlet, provided that the wires are held next to one another, as is typical. If, however, the two conductors are separated, as in high tension wires, substantial magnetic fields are produced around each wire.

The size of the magnetic field is a linear function of both the size of the source generating the magnetic field (the distance between the three conductor wires of a transmission line on a steel tower, the size of coil inside an electric motor) and the amount of current flowing through the wires.[59,68] Therefore, if one doubles the size of the source generating the field (for example, by increasing the space between the wires on the towers), the strength of the magnetic field will double. Similarly, if one doubles the amount of current, the strength of the magnetic field will be doubled.

In addition, magnetic fields fall off rapidly with distance from their source, typically as the square of the distance.[59,68] Therefore, as one moves away from an overhead transmission line, the magnetic field falls by a factor of four for every doubling of the distance from the source. For example, if the field at 50 feet from the transmission line tower is half that at the tower, then at 100 feet it is approximately one-quarter that at the tower. Several hundred feet away from even the largest power line source, the magnetic field due to these lines become relatively small due to this exponential decay.

If one combines the principles regarding the size of the generating source and the distance from the generating source, one can compare the exposure potential from different sources. For example, immediately next to a small electric appliance such as a microwave oven, the magnetic field may be in excess of 1000 mG, substantially larger than the maximum magnetic field measurable under the electric power distribution system wires outside your house. However, the magnetic field from the appliance falls off to below 1 mG within a few feet, while that from the power lines can extend several hundred feet from the source because the source is much larger.

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the greatest risk to residents. This hypothesis has yet to be confirmed physically or tested epidemiologically.

A third limitation of these studies is the possible influence of bias. That is, subjects may not have been selected in a balanced manner, characteristics of subjects may vary by disease status (such as length of residence at a particular location), and exposure information and other risk factors may not have been collected with equal success in both cases and controls. In spite of these concerns, it is unlikely that they can be responsible for the positive results found.[28,29]

Occupational Exposure and Cancer Studies. Interpretation of most of the occupational epidemiology studies is more problematic than interpretation of the residential exposure studies. The occupational studies are subject to imprecision in occupational exposure assessments—using job titles—and the lack of information for statistical control for other workplace exposures (see Savitz and Ahlbom[6] and Theriault[30] for recent reviews). Milham, a longtime analyst of Washington State's vital records data, conducted the first occupational assessment of magnetic field exposure and cancer by reviewing the causes of death of those employed in electrical occupations. He found that adult radio operators and others in electrical occupations had excess risk for leukemia deaths.[31,32] Following the publication of these results, many researchers conducted similar studies comparing the rates of cancer incidence and mortality for people employed in different occupations. Fairly consistently, the researchers found excess leukemia and nervous system cancers in those who worked in occupations in which there was substantial use of electricity (electricians, electric utility line workers, power company employees, telephone line repairers). These studies, however, are limited in that: *(a)* the exposure characterization is very general and may not apply to specific individuals; *(b)* other workplace exposures to carcinogens, such as solvents, are not accounted for; and *(c)* personal habits and behaviors, such as exposures related to residence or hobbies and other activities, are not adjusted for. Nonetheless, the results of these studies are consistent with the childhood cancer residential exposure studies (tables 1–3).

To improve on the earlier research, four recent occupational studies included a series of job task exposure measurements in their exposure assessments.[33-36] Of these studies, all but one—of Southern California Edison workers[34]—found elevated leukemia and brain cancer rates, but not all findings were statistically significant. The specific risks varied from 0.9 to 1.5 for leukemia and from 1.1 to 1.7 for brain cancer. A disparity among the studies is the relative importance of leukemia and brain cancer risks; Floderus et al.[33] and Theriault et al.[35] found the higher risk for leukemia, while Savitz and Loomis[36] found the higher risk for brain cancer. In general, results are similar to those using only job titles (tables 1–3). Recent meta-analyses summarize the results of studies on the association between occupational exposures and brain cancer and leukemia[37,38] and report modest but statistically significant increases in cancer risks associated with exposure to magnetic fields.

Another provocative result found in a small set of occupational studies is a reported association between inferred magnetic field exposure and the incidence of male breast cancer.[39-42] This association had been hypothesized several years earlier as resulting from a hormonal response.[43] A recent study, however, failed to further corroborate this association.[44] Because of the rarity of this disease (about 1 in 50,000 men per year), investigation opportunities are very limited and results are controversial.

Epidemiologic Studies of Non-Cancer Effects. There has been limited epidemiologic research on potential EMF-related outcomes other than cancer. Reproductive effects have been looked at for a variety of exposure scenarios ranging from electric blankets to occupation to video display terminals (VDTs). Although many studies have looked at VDT exposures in the workplace, evidence for a strong association is lacking.[45] Evidence for other exposures is sparse although largely negative, suggesting the absence of a strong effect.[45,46]

Neuropsychological and behavioral effects from magnetic field exposures also have been studied.[47] In sum, the study of neurobehavioral responses to electric and magnetic field exposures is inconsistent and of mixed quality. The

Table 3. Summary of epidemiologic studies on EMF exposure and lymphomas

Exposure activity	*Population studied*	*Exposure metric*	*Number of studies*	*Number reporting positive results*	*Number reporting statistically significant positive results (P<0.05)*	*Average risk[a] ratio*	*Range of risk ratios*
Residential	Children	Wire codes and distance	2	1	0	1.3	0.8–2.5
		Spot measures	2	2	0	2.0	1.7–2.2
		Calculations	3	2	0	1.0	0.0–5.0
	Adults	Wire codes and distance	2	2	0	1.4	1.3–1.5
		Spot measures	1	1	0	2.0	—

[a]Average risk is defined as the weighted geometric mean of estimated odds ratios, where the weights are the inverses of the estimated variances.

NOTE: Studies that use more than one method of exposure assessment are counted more than once.

exposure measures used—job titles, calculated fields, spot measures, and visual proximity—all have known limitations and likely result in substantial misclassification. The outcomes studied include suicide, depression, and neuropsychological performance but were reported inconsistently in studies that looked at a wide range of reported symptoms, and only some of the studies used standardized instruments to assess their occurrence. The studies are plagued by low response rates and possible bias due to variations in educational level and socioeconomic status among subjects. No clear association has been found.

Finally, a recent occupational study has found an increased occurrence of Alzheimer's disease in three cohorts.[48] Researchers looked at tailors and seamstresses and found the increased disease associated with extremely high magnetic field exposures from sewing machines (adjusted odds ratios from 1.7 to 10.2). Most results were not statistically significant because of the small numbers of exposed subjects in each cohort stratified by gender (from three to 29). These studies need to be replicated independently.

Laboratory Studies. Some of the most compelling evidence that can be used to confirm a purported causal relationship between a specific exposure and a disease is a set of studies that show similar effects across different biological systems. Following the publication of the first epidemiological studies showing an association between exposure to magnetic fields and human cancer, there was a large increase in laboratory studies of this phenomenon. Two types of investigations were undertaken. Laboratory studies of cell cultures exposed to magnetic fields and traditional toxicological tests of animals raised in magnetic fields have, in general, not substantiated the findings of the epidemiologic studies. That is, while epidemiologic studies have shown positive associations that often are statistically significant, most laboratory studies have not. Further, while some associations were detected in the laboratory, it is not clear that these effects are indicative of adverse human health effects (such as altered gene expression).

By and large, both the *in vitro* (cellular) and *in vivo* (whole animal) studies are negative, with a few notable exceptions. One of the difficulties in conducting these studies is the maintenance of the appropriate magnetic fields in each of the respective exposure groups. In addition, spurious types of interference can result in positive findings. Therefore, the standard of acceptance for *in vitro* studies is typically the replication of a given observation by a laboratory unconnected with the authors who originally reported the results. Of the *in vitro* studies conducted at magnetic fields typical of environmental exposures (usually up to 10 mG), a limited number have reported positive results, but the results have not been replicated by independent laboratories. The vast majority of these *in vitro* studies reported negative results. Studies conducted at higher magnetic field strengths (such as 1 G) report reproducible gene effects but not genotoxic effects. At still higher exposures (such as 5 G), intracellular calcium effects and general changes in gene expression are found, but still no genotoxicity.

The focus of more recent animal studies exploring the

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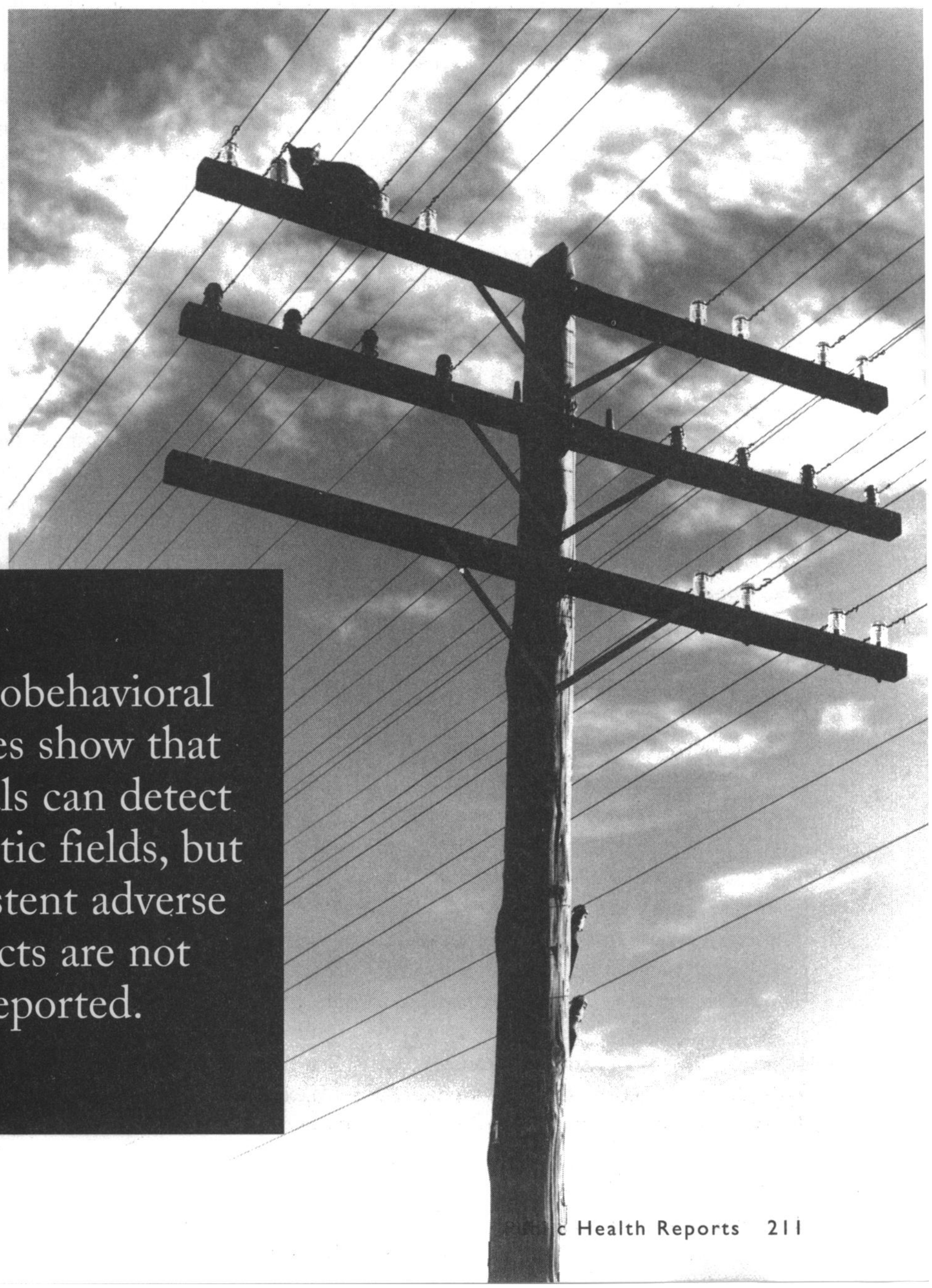

Neurobehavioral studies show that animals can detect magnetic fields, but consistent adverse effects are not reported.

How Exposure is Assessed

In order to fully understand the findings of studies on the health effects of magnetic fields, we need to understand how researchers have measured human exposure.

Residential Exposures. The methods that epidemiologists use to assess exposure of study subjects to magnetic fields have evolved as more and more studies have been conducted. Generally speaking, a person's exposure to magnetic fields is a function of the amount of eletrical current flow, the size of the generating source, and the subject's proximity to the magnetic field. The first generation epidemiologic studies of residential exposures focused on power line magnetic fields rather than those from more transient sources such as appliances. Instead of directly measuring the magnetic field inside a home, researchers devised a quick and relatively simple system of categorizing the expected magnetic fields—wire coding—based on the diameter and type of wires outside the home (a crude estimate of the size and the current flow) and their distance to the home (to estimate the fall off of the magnetic field).[7] This exposure metric combined two aspects of magnetic field exposures[7,8]—distance from the line and current on the line—while other studies limited the exposure assessment to the distance of the subject from the lines.[13–16,19,20]

The second generation of residential studies used measurement devices that recorded the instantaneous, or "spot," magnetic fields.[10–12,21] These data were intended to estimate what a person living in the residence was exposed to. Yet this method fails to measure both temporal fluctuations in electrical currents (daytime versus nighttime, summer versus winter) and differences between individuals' daily activity patterns, thereby adding substantial errors to these numbers.

Three epidemiologic studies provided data for both wire coding and spot measures, enabling limited comparisons to be conducted,[11,12] and some studies were conducted simply to compare methods of exposure assessment.[21,] In general, in spite of its simplicity, the wire coding system has proved to be moderately predictive of long-term average magnetic field exposures.[71–73] Modifications of the coding system designed to improve the association of a metric with adverse health outcomes have been proposed.[74] Nonetheless, some scientists question the validity of these modifications and of the original wire codings system itself.[75]

The third generation of residential studies estimated past exposures using historical data on line loads (average current flows) and proximity of residences to the power lines.[21–23] These, too, have limitations in that the data typically used are annual averages, peoples' activity within the home were not assessed, and nonresidential exposures (at the workplace or from hobbies) were not assessed. Nonetheless, this approach, using electric load data takes us one step closer to the actual magnetic fields experienced by the study subjects.

The fourth generation of residential studies, the first of which is currently being undertaken, use personal monitors for each subject. A small magnetic field recording device is given to each child being studied; the device characterizes the magnetic fields that each child experiences on sample days and the length of time the child is in each magnetic field. The measurements are combined with the time-activity patterns of a child to develop a cumulative exposure estimate. As a less cumbersome alternative, Kaune et al.[76] conducted a study to determine whether adequate exposure information could be developed without having children wear personal monitors. They found that they could explain about 80% of the variability in exposure data by combining spot measurements of magnetic fields in the home, 24-hour measurements of magnetic fields in the home, and wire coding data.

A few exposure studies have focused on appliance usage.[77,78] Some epidemiologic studies used subject-reported data on whether or not they had used particular appliances, and some used subject-reported frequency-of-use data. However, these epidemiologic assessments did not all look at the same appliances or adverse health outcomes, precluding meaningful interpretation.[12,79–83] Nevertheless, some surprisingly large and statistically significant odds ratios were reported.

Occupational exposures. Building on decades of fruitful studies of occupational health hazards, the first generation of occupational epidemiology studies compared health outcomes of groups reporting different occupations. While these data are fraught with problems—including inaccurate reporting, missing information, failure to capture more than one lifetime occupation, and lack of differentiation among job tasks and exposures within the job title—there is an extensive literature linking job titles with specific adverse outcomes. Many of these associations were later verified with more focused epidemiologic studies, including specific exposure measurements.

To study occupational exposure to magnetic fields, researchers classified job titles according to whether the individual would likely be exposed to magnetic fields—for example, electrical engineers, electrical equipment assemblers, electrical line repairers, and telephone operators—or not.

More recently, a series of studies have estimated worker exposures by providing workers with personal monitors, determining typical exposures for specific job tasks using these data, and multiplying these exposures by reported time (usually measured in years) spent at each job task.[33–36] These studies combined work history, activity patterns, and job-specific magnetic field measurements to provide a quantitative estimate of magnetic field exposure.

possible carcinogenicity of EMF exposure has been the role of EMF as a promoter. Studies that investigated skin and liver tumors were, in general, negative. Studies investigating breast tumors, however, have produced some suggestive results. Beniashvili et al.[49] found that animals exposed to N-nitroso-N-methylurea showed an increased rate of mammary tumors when subsequently exposed to 200 mG for a half hour per day. Löscher and colleagues[50,51] conducted a series of studies on rats in which the experimental animals were exposed to the cancer-initiating compound DBMA (7,12-dimethyl benz[a]anthracene) and then exposed to magnetic fields. At 300 mG, one study showed increased numbers of tumors per tumor-bearing animal while a replication study did not. At 1 G, studies showed an increased rate of mammary tumors. Including results from as yet unpublished studies, Löscher reports that these data show a dose response.[52] These results, while limited, are particularly intriguing in light of a proposed hormonal mechanism of action[43] and of the results of occupational epidemiologic studies of breast cancer.[39-42,44,53]

Laboratory studies of reproduction and development do not show adverse effects.[54,55] Neurobehavioral studies show that animals can detect magnetic fields, but consistent adverse effects are not reported.

It is important to note that experimental studies are generally conducted at magnetic fields levels far above those encountered in the environment. This practice is consistent with the testing of chemicals because the size of each of the experiments is severely limited by logistics (typically a maximum of 50 individuals at any dose level). For studies with positive results, statistical methods are used to extrapolate the data down to typical environmental exposure levels. Therefore, while many critics argue that even positive results at these exposures would not be relevant for consideration of low-level environmental exposures, extrapolating effects from high exposure laboratory studies is the accepted norm for assessing chemical hazards.

Summary of Health Effects Studies

Summarizing the scientific investigations of the human health effects of exposure to power frequency magnetic fields is difficult because of the inconsistencies in results. There is as yet no suggestion of a plausible mechanism by which these magnetic fields could induce cancer in human systems, save that for breast cancer. However, it is not uncommon for epidemiologic results to precede the development of appropriate mechanistic data. For example, even though we know that a diet rich in fruits and vegetables decreases one's risk of cancer and heart disease, in general studies of specific vitamins have failed to show comparable benefits and have not elucidated the biological mechanisms of action.

Laboratory studies of magnetic field effects have not shown strong support for an association, although there are some provocative and intriguing data. Again, some carcinogens (benzene, for example) were demonstrated in epidemiologic studies long before laboratory studies were able to provide complementary results.[56] In addition, the technical intricacies of providing an accurate and stable magnetic field environment in the laboratory have compromised the findings of many studies, both positive and negative.

From the epidemiologic perspective, the lack consistency in statistical results has also compromised the interpretability of the studies. The investigation of the magnetic field issue is frustrating. Usually, in the evolution of the study of a problem, increasingly sophisticated designs and exposure assessments have led to a clearer understanding of the problem. In this case, the picture continues to be unclear; most studies report positive findings, but across studies these findings are not consistent for any specific health effect. Generally, as with most carcinogens, higher exposure seems to lead to greater effects; however, the hypothesized dose-response relationship needs to be better characterized.

In total, the epidemiologic data on both residential and occupational exposures show a moderate risk of cancer, generally between 1.1 and 3.0, for adults and children exposed to magnetic fields. This is not extremely large relative to other known risks (for example, the smoking-related risk of approximately 10 or the asbestos-related risk of 5). However, what is unusual about magnetic field exposures is that they are universal. Virtually all of us are exposed, at home, at work, during recreation, and elsewhere. This means that: (*a*) the observed risk may be underestimated because we cannot identify a truly unexposed comparison group; (*b*) because of the widespread exposure, even a small risk may result in a large number of individual cancers.

Implications for Public Policy

One of the challenges of developing public policy is to ensure that policy decisions are responsive to the state of scientific knowledge. For the problem of exposure to magnetic fields, this means assessing the likelihood of a causative relationship between exposure and disease and, if found, assessing the degree of risk to an individual and the prevalence of exposure. Causation is assessed by considering characteristics of known causative relationships, including the sensitivity, specificity,and strength of the association; the replicabilty of study results within and among different biological systems; evidence of a dose-response relationship; and the plausibility of a biologic mechanism.[57] From the above review, it is evident that the body of information on magnetic field exposures shows some characteristics that support a causal association, but not all. Interpretation of the data vary widely among scientists, policy makers, and the public. Therefore, in what follows we consider three different strategies for responding to the problem, each reflecting a different assessment of the strength of evidence for a causative association.

The implications of the magnetic field debate for public policy are great. Controversy exists as to whether society is responding appropriately given the severity of the potential risk and the quality and consistency of the data. Even among those with similar interpretations of the scientific data, there are often differences of opinion about the most appropriate policy response. To evaluate these, it is necessary both to understand what can be done to reduce exposure and to have some estimate of the cost involved. Precise cost estimates are not easily available. The utilities' financial data, even when submitted to regulatory agencies, are typically not disaggregated to reflect the cost of individual lines. Further, because prices are affected by the specifics of the line and locale being considered, precise costs are hard to estimate.

There are two main approaches to lowering exposures to magnetic fields: personal and societal. On a personal level, one can move electrical appliances away from one's night table, use regular blankets or comforters instead of electric ones, and try to keep one's distance from appliances such as toasters, microwave ovens, and televisions. These actions all lower one's exposure without incurring a substantial cost or inconvenience.

On a societal level, minimizing the population's exposure to magnetic fields is more challenging. The basic physics principles of magnetic fields can be used to yield some straightforward methods for magnetic field reduction and mitigation of exposure. (See Basic Properties of Magnetic Fields on page 209.)

First, where possible, magnetic fields can be balanced, or nearly balanced. Engineers have proposed methods for constructing electric power transmission lines that are partially or fully balanced: phasing and split-phasing.[58,59] When neither is possible, magnetic fields can be cancelled to a lesser degree by specific arrangement of the three wires constituting a transmission line. For example, the configuration with the least cancellation is called a horizontal configuration; the three wires of the transmission line are strung in a plane parallel to the ground. An improvement over this, in terms of horizontal spread of the magnetic fields, is the vertical configuration, in which the three wires are strung in a plane perpendicular to the ground. With this configuration, the magnetic fields within 100 to 200 feet of the line are typically reduced by 10% to 30% compared with the horizontal configurations at little or no extra cost.[58] A further improvement is the delta configuration, in which the three wires are strung in a triangular arrangement. The magnetic fields typically are reduced by 30% to 60% at a cost increment of up to 20% relative to the horizontal configuration.[58]

Second, the source of the magnetic fields could be reduced in size by compacting the wires, that is, by placing them closer together. The principal concern with this practice is that if the three wires of a transmission line are placed too close together, a spark will jump between the wires and short out the entire line. New approaches to insulation are required for this approach to be effective.

Third, for electric power transmission systems, one could increase the distance of the source from people. This can be done by increasing the height of the towers holding the wires or by increasing the distance of the towers from people (for example, by increasing the width of the right-of-way, the buffer zone that runs along a transmission line corridor). However, taller towers are expensive and may create aesthetic problems, and increased rights-of-way may not be possible due to existing construction or may be very costly.

Fourth, one can consider placing the lines underground. Magnetic fields drop off at a substantially shorter distance from most underground lines than from most overhead lines. While many assume that this is because the magnetic fields dissipate more rapidly underground, in fact it is because the wires are placed within a few inches of each other underground and packed in nonconducting material such as oil, resulting in a much smaller source than the several feet apart system of wires hanging on towers. However, because the lines are underground, people can walk over them, resulting in high exposures due to close proximity. Further, the cost of building and maintaining underground lines is reported to be several times that of above-ground lines, even though underground lines have fewer maintenance problems.[58]

In light of this information, we consider three policy strategies for responding to concerns about adverse human health effects from magnetic fields: *(a)* the fiscally conservative approach: provide information but take no action; *(b)* the cost-benefit approach: minimize new exposures where this can be done at limited cost; *(c)* the aggressive exposure reduction approach: limit all exposures.

The Fiscally Conservative Approach: Provide Information But Take No Action. Some argue that both concern and action are unwarranted in light of the currently available data. That is, while the data might indicate a hazard, the information is too inconsistent at this time to warrant the substantial expenditures that would be necessary to reduce exposures. For example, the American Physical Society has argued that several billion dollars have been spent to date to minimize exposure to electric and magnetic fields and that, in light of the inconsistent scientific data, this level of "funding and public attention" is incommensurate with the risk.[60,61] They recommend that no further actions be taken and believe that resources directed toward the EMF problem could be spent more effectively elsewhere.

Utility companies, in general, take a similar view, arguing that it is premature to reach a judgement on causation and hence regulation. Responding to public concerns, however, many individual utility companies have gone one step further by offering their ratepayers the opportunity to have their residences surveyed for magnetic fields and to discuss the results with a utility representative. A similar perspective has been voiced by Florig,[62] who estimates the economic impact of current magnetic field mitigation measures as over $1 billion per year. In light of the contradictory scientific data, he argues for further research to resolve the health effects controversy, although he suggests that broadscale measures to further reduce exposures may be premature.

Taking a fairly passive stance with respect to the causative relationship between magnetic fields and adverse human health effects, the Environmental Protection Agency and the Department of Energy have developed public documents that discuss the controversy, review the scientific data, and summarize what is currently known about health risks. While there are differing opinions about the accuracy, bias, and understandability of these documents, each seeks only to inform the public and implicitly recommends against a societal response at this time.

The Cost-Benefit Approach: Minimize New Exposures at Limited Cost. Some scientists believe that while the data are inconclusive, the risk is sufficiently large and the exposure is sufficiently widespread that actions to limit new exposures are warranted. Further, with proper planning this can be done at limited cost. One option is to impose a moratorium on the construction of new transmission lines. This was proposed in but not passed by legislatures in Illinois, Indiana, Ohio, and Rhode Island.[63] Less severe restriction has been implemented by Texas, Colorado, and Wisconsin, under which utilities are urged to include land use considerations as part of planning the location of new electric power transmission lines.[64] These states want utilities to consider routing new lines away from highly populated areas—particularly to avoid structures frequented by children, such as schools and playgrounds—and to use "low EMF designs." This can often be done at either no cost or at a small cost increment. Colorado has even suggested that utilities consider magnetic field reductions costing as much as $1000 per individual likely to be exposed.

In California, there has been much public concern and discussion about the EMF issue. As a result of a series of meetings and interested party workshops, the California Public Utilities Board has issued a ruling allowing utilities to spend up to four percent of the construction costs of a new transmission line on magnetic field reduction. This will enable but not require the utilities to consider alternative practices that will limit new exposures while still providing the desired electrical power.

In New Jersey, the Commission on Radiation Protection is considering implementing a regulation that will require utilities, when constructing new electric power transmission lines, to ensure that the exposures within the right-of-way are at least 50% lower than the worst case (single circuit, horizontal configuration) exposures. Depending on the line characteristics, this can be done at between no additional cost and 20% additional construction costs (for example, by using a delta configuration).

Finally, some researchers have suggested consideration of cost-benefit decision-making strategies.[64,65] In these endeavors, researchers compare the relative cost of alternative power line construction or mitigation policies with the number of people exposed or the degree of exposure. Interested parties could suggest relative weights and priorities to be used in such evaluations.

The Aggressive Exposure Reduction Approach: Limit All Exposures. Some people are so concerned about the adverse health effects attributed to magnetic fields that they are calling for an immediate reduction in exposure. Activists typically recommend a magnetic field limit at the edge of the power line rights-of-way of 2 to 3 mG,[66,67] a level likely derived from numbers reported in epidemiologic studies. There has been no systematic evaluation of the cost or health impact of such a strategy.

Two states have implemented policies that limit the maximum exposure to magnetic fields from electric power transmission lines. Both New York and Florida have issued regulations requiring that the measured magnetic fields at the edge of the right-of-way of an electric power transmission line be less than 200 mG. Many point out, however, that this exposure level is so high that most lines in the United States already meet this regulation and thus its implementation has had no effect.

Activists recommend strategies for both personal and general reduction of magnetic field exposures. Two recent books on this topic provide detailed descriptions of how individuals can reduce their exposures at home and in the workplace while also providing strategies for addressing issues of power line magnetic fields and other sources of nonionizing electromagnetic radiation.[66,67] Government and regulatory bodies have been reluctant to implement these strategies. Instead, many of the debates are being carried out in the courts.

Conclusions

Overall, concerns about magnetic fields and power lines reflect a complicated and confusing public health controversy. The science is indeterminate. Individual studies often meet the scientific criteria for acceptability, but when taken together, the literature shows considerable inconsistency and contradiction. The problem of how to define biologically relevant exposure is paramount to a better understanding of the issue, and the identification of a possible mechanism of biological action would be extremely useful.

In the short term, I would recommend several strategies that can be used to improve our understanding of this issue and help resolve the controversy. Biologically, it would be useful to conduct studies looking for precursors of leukemia among individuals highly exposed to magnetic fields. The emphasis on cancer, a relatively rare disease, has focused epidemiologists on studies with limited statistical power to detect associations. In terms of exposure, further work needs to be done on defining a biologically relevant metric of exposure and resolving the differences and epidemiologic inconsistencies between wire codings and magnetic field measurements. In the laboratory, there needs to be further replication of intriguing results and confirmation or refutation of possible association. Finally, overall, this field would benefit greatly from improved integration of studies across disciplines. Identifying clues from the laboratory might spur epidemiologic hypotheses, while laboratory investigation of ideas generated from specific epidemiologic results might aid our understanding of the mechanism of biologic activity.

Until clarifying results are obtained, governments must make a decision as to which, if any, regulations or policies are warranted. Formal risk assessments, as some call for, are difficult to interpret in light of the imprecise and sometimes contradictory study results. In my view, in light of the positive data, limited action is called for. Whether the underlying risk factor for the observed childhood leukemias is magnetic field exposures or not, the evidence shows that these cancers are indeed correlated with high wire codings and thus possibly with the presence of magnetic fields. Therefore, where we can reduce exposures at low cost and low inconvenience, we may substantially reduce future disease. Even if the association proves spurious, this strategy of limited, low-cost action will not have had a large impact on society.

Dr. Wartenberg is an Associate Professor of Epidemiology with the Environmental and Occupational Health Sciences Institute, Robert Wood Johnson Medical School, University of Medicine and Dentistry of New Jersey.

Tearsheet requests to Daniel Wartenberg, EOHSI, P.O. Box 1179, 681 Frelinghuysen Road, Piscataway, NJ 08855-1179; tel. 908-445-0197; fax 908-445-0784; e-mail <dew@EOHSI.Rutgers.edu>.

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