# The Rise and Fall of Power Line EMFs: The Anatomy of a Magnetic Controversy

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**Abstract**

*The suggestion that power line electromagnetic fields (EMFs) cause diseases like cancer has generated dozens of popular articles and television news segments, hundreds of scientific studies, and numerous consensus reports; it has attracted the attention of epidemiologists, biologists, physicists, policymakers and lawyers. This article will examine the evolution of this controversy through a detailed analysis of the arguments that have been used for and against the hypothesis that power line EMFs have adverse health effects. This article argues that the power line EMF issue provides a classic case study for exploring the challenges citizens, scientists, and policymakers face in sorting out a complex science-based controversy. This story not only brings together many different perspectives and—from popular notions of cancer clusters to complex epidemiological arguments, from to state-of-the-art animal studies to policy instruments such as the precautionary principle—but also reveals the manner in which a heated controversy can be effectively resolved over time.*

In the late 1980s, Paul Brodeur, a journalist who helped break the story linking asbestos with cancer, stumbled on what he believed was an even bigger environmental scandal—power line electromagnetic fields (EMFs). In a series for *The New Yorker* called "Calamity on Meadow Street" (Brodeur, 1990a), Brodeur wrote of how the citizens of one street in Guilford, Connecticut, located next to an electricity substation, suffered from a "dramatically higher incidence" of cancers. In another series, "The Slater School" (Brodeur, 1992), Brodeur featured an elementary school situated close to power lines in Fresno, California, where 15 teachers and staff members had developed cancer in recent years.

Brodeur, who wrote two popular books on the subject, *Currents of Death* (Brodeur, 1989a) and *The Great Power Line Cover-up* (Brodeur, 1993), warned that power line EMFs were a pernicious environmental toxin being covered up by powerful energy interests. The story resonated with other journalists (Bradley, 1993; Brokaw, 1990; Jennings, 1987, 1993a, 1993b; Koppel, 1990; Rather, 1990a) and attracted the attention of tort lawyers. For example, lawyers for the Bullock family brought suit against Connecticut Light and Power charging that the substation in Meadow Street where they lived had caused Melissa Bullock's brain tumor.

The scientific investigation of power line electromagnetic fields had already begun in 1979, with a pioneering epidemiological study carried out by psychologist Nancy Wertheimer and physicist Ed Leeper (Wertheimer & Leeper, 1979). Wertheimer and Leeper compiled a list of children in the Denver area who died of any form of cancer during the period 1950–1973 and compared them with an equal number of controls—children without cancer—randomly selected from birth records. To estimate the electromagnetic field exposure they used a "wire configuration code" whereby, depending on the distance of a home to a substation or power line and configuration and thickness of the wires, they assigned the homes to one of five exposure classes. The results showed children in high wire configu-

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ration homes died of cancer at about three times the rate of those in the lowest wire configuration homes.

The combination of Wertheimer and Leeper's epidemiological study and Brodeur's high-profile journalism succeeded in establishing power line EMFs as a credible public health issue worthy of scientific study. In the decades since, over 100 epidemiological studies have been published (Foster, Erdreich, & Moulder, 1997; Moulder, 2005; Moulder & Foster, 1999) including both "occupational" studies of workers such as linemen and cable splicers—whose job potentially exposes them to high electromagnetic fields—and "residential" studies, investigating whether people living near power lines or substations are at increased risk for disease. In addition, scientists have carried out numerous animal and in-vitro studies in an effort to parse any biological effects of power line magnetic fields, funded in part with a special $65 million initiative (the EMF RAPID program[1]), overseen by the National Institute of Environmental Health Sciences (NIEHS).

The controversy has grown to include not only epidemiologists, biologists, journalists, EMF activists, the utilities, and personal injury lawyers, but also electrical engineers and physicists—who feel that their expertise in electromagnetism entitles them to participate—and policymakers and social scientists who have debated the applicability of the precautionary principle[2] to this dispute. There's a lot at stake. Some 2 million miles of power lines cross America, carrying electric power from power stations to substations and from substations to people's homes. If there is a danger, it is pervasive and expensive to mitigate. After all this science and deliberation—culminating in numerous consensus reports[3]—what has been learned?

This article will examine the evolution of this controversy through a detailed analysis of the arguments that have been used for and against the hypothesis that power line frequency EMFs have adverse health effects. In some ways, the power line EMF issue provides a classic case study for exploring the challenges citizens, scientists, and policymakers face in sorting out a complex science-based controversy. This story not only brings together many different perspectives and approaches—from popular notions of cancer clusters to complex epidemiological arguments, from state-of-the-art animal studies to policy dilemmas—but also reveals the manner in which a controversy changes over time, as the various actors are forced to respond to arguments and evidence.

## The Demise of the Texas Sharpshooter: From Cancer Clusters to Epidemiology

As discussed, the classic media depiction of this controversy focuses on the occurrence of mysterious cancer clusters. When making a documentary on power line EMFs, *Frontline: Currents of Fear* (Palfreman, 1995), I witnessed the genesis of such a cancer cluster in Omaha, Nebraska (Thomas, 1994; Thomas, 1995). The film starts by showing how a group of mothers become convinced that their children's leukemia has an environmental cause. One of them, Dee Hendricks, puts it this way, " I knew, instantly, that this was not a normal thing going on. I wondered what it was in my neighborhood or in Omaha that could have possibly caused my son to have cancer. And driving home one night, I noticed that there were huge transmission towers that were scattered throughout the neighborhood" (Palfreman, 1995, 03:24).

Dee connects with other concerned mothers and, after watching a story on power-lines and cancer on the CBS show *Street Stories* (Bradley, 1993), the group becomes convinced that power-line fields are to blame. Finding little sympathy at the health department, they take matters into their own hands, plot their community's cancers on a map, and conclude that there are four Omaha zip codes, criss-crossed with power-lines, that appear to have two to three times more cancer than average. This narrative is along the lines of Brodeur's "Calamity on Meadow Street" story. It makes for compelling journalism. But have the Omaha mothers really found a disturbing causal relationship or have they unwittingly fallen into a classic methodological error sometimes called the "Texas Sharpshooter" fallacy?

As epidemiology students learn, the Texas Sharpshooter is a less than honest cowboy who fires his gun at the side of a barn and then afterward draws in the target in such a way to make him look like a decent marksman. In other words he does not decide his target in advance, only in retrospect. Instead of scattered bullets, think of cancers occurring randomly across the country in all areas, year in year out. Now artificially draw boundaries in space and time—a zip code, a street, a decade, a generation—and look to see if anything pops out. You will, just by chance, find some streets with more cancer cases than average (such as Meadow Street or some areas of Omaha), and it is human nature to presume that the "cluster" is meaningful. But, unless you look comprehensively at all zip codes, you might miss the fact that other streets and zip codes have *less* than the average number of cancers. An investigator, or a policymaker, who ignores the areas and periods with "less cancer" and only selects those with "more cancer," is no better than the Texas Sharpshooter. Cancer clusters by themselves, therefore, rarely settle the matter, a more systematic gathering and analysis of data is necessary.[4]

Indeed, the very discipline of epidemiology was developed precisely to try to avoid such fallacies and distinguish real effects from simple coincidence. But as will be seen, professional epidemiology is plagued with its own controversies about quantitative reasoning, and these experts would be accused of statistical "sharpshooting" as well.

## Epidemiology and Its Limits

Epidemiology is traditionally the study of epidemics. It comes from the Greek words *epi* meaning "upon," and *demos,* "the people." Epidemiologists, who are frequently the first scientists on the scene of a new public health issue, have had some legendary successes: from John Snow, the London physician who in 1854 traced a London cholera outbreak to a contaminated water source (a pump on the corner of Broad Street and Cambridge Street), to the Center for Disease Control's unraveling of the etiology of AIDS in the 1980s. It was teams of epidemiologists who uncovered the link between smoking and lung cancer and who discovered the cause of Legionnaire's disease. But was this science powerful enough to prove or disprove a causal link between power lines and human disease?

Since Wertheimer and Leeper's study, epidemiologists have certainly made a concerted effort to shed light on the controversy. As mentioned, well over a

**Table 1.** Epidemiological Studies of Cancer and Occupational Exposure to Power-Frequency Fields

| Type of Cancer | No. of Studies | Median RR | Range of RR's |
|---|---|---|---|
| Leukemia | 45 | 1.20 | 0.80–2.10 |
| Brain | 35 | 1.15 | 0.90–1.90 |
| Lymphoma | 12 | 1.20 | 0.90–1.80 |
| Lung | 15 | 1.05 | 0.65–1.45 |
| Female Breast | 10 | 1.10 | 0.85–1.50 |
| Male Breast | 10 | 1.25 | 0.65–2.80 |
| All Cancer | 15 | 1.05 | 0.85–1.15 |

**Table 2.** Cancer and Residential Exposure to Power-line Fields

| Type of Cancer | No. of Studies | Median RR | Range of RR's |
|---|---|---|---|
| Childhood Leukemia | 20+ | 1.20 | 0.80–1.90 |
| Childhood Brain Cancer | 10+ | 1.20 | 0.80–1.70 |
| Childhood Lymphoma | 8 | 1.80 | 0.80–4.00 |
| All Childhood Cancer | 7 | 1.30 | 0.90–1.60 |
| Adult Leukemia | 6 | 1.15 | 0.85–1.65 |
| Adult Brain Cancer | 5 | 0.95 | 0.70–1.30 |
| All Adult Cancer | 8 | 1.10 | 0.80–1.35 |

hundred epidemiological studies on the health effects of power line frequency EMFs have been published. Some studies (Savitz, 1988; London, 1991) claim to have found associations with disease, others (Linet, 1997; McBride et al., 1999) have failed to find any relationship. Because there are so many studies, it is helpful to take a snapshot of all of them. Radiation biologist John Moulder has prepared such a big-picture perspective that is reproduced in Tables 1 and 2 (Moulder, 2005): one table represents the occupational studies; the other residential studies. While these studies incorporate different methodologies, different methods of measuring field exposures, and different disease end points, all of them end with a number, a so-called risk ratio (RR). This number claims to estimate the average risk of an exposed individual as compared to an unexposed (or less-exposed) one. A risk ratio of more than one suggests an increased chance of acquiring, say, a cancer, a risk ratio of less than one suggests a possible protective effect of the EMFs.

The fact that many of the studies show risk ratios of more than has convinced Brodeur that the verdict is in and the United States faces an urgent public health problem. "You literally have millions of unsuspecting men, women and children exposed to power frequency magnetic fields that have already been associated [with cancer] in dozens upon dozens of studies conducted and published in the peer reviewed medical literature" (Brodeur, quoted in Palfreman, 1995, 06:36).

But just because the median risk ratio rises above 1.00 does not prove a causal relationship between power line EMFs and cancer. The positive associations could be due to many other factors such as confounders, inadequate dose measurement, and statistical artifacts. The methodological issue of determining whether there is truly a causal relationship between an agent (such as power line fields) and a disease (such as leukemia) is complex and controversial (Hill, 1965; Moulder, 2005; Taubes, 1995). In 1965, the British epidemiologist Sir Austin Bradford Hill proposed a straightforward way to approach the correlation versus causation question. Hill delineated a test in the form of a set of criteria that, he argued, should be fully or partially met before scientists could conclude that there was a causal relationship between agent and disease. This article will use Hill's criteria to test the case for and against power line EMFs.

### *The Hill Criteria*

Hill believed that epidemiology alone could establish causation provided three criteria were met: one, the association between alleged agent and disease was strong; two, the effect was consistent, that is, the same disease was seen consistently in different studies; and three, the size of the effect increased with dose.

Most important, said Hill, was the *strength* of the association between the hypothesized agent and disease. Strength alone, in Hill's view, was sufficient to establish causation. One of the clearest modern examples of a strong association is smoking and cancer. In his work with the epidemiologist Sir Richard Doll, Hill found that a pack-a-day smoker is 14 times more likely to develop lung cancer than a nonsmoker. This number—the so-called risk ratio—is large. Moreover, Doll and Hill found that the risk of lung cancer increased with increased dose. Smokers who consumed two packs a day were at higher risk, and three pack-a-day smokers at even higher risk. This effect, a so-called *dose response*, Hill argued, was also strong evidence of causality. Because a single study cannot be relied on as definitive, Hill said, an association should be found *consistently*; other investigators working independently should be able to reproduce the results.[5] All studies of smoking found an association with lung cancer, for example.

But what if the epidemiological evidence does not show this profile? What if, for example, the epidemiology yields risk ratios less than 5, and the different studies are inconsistent and show no dose response? Then, said Hill, epidemiology alone could not be relied on to prove causation. As an epidemiologist, Hill knew that it was all to easy to generate weak associations that looked real but were in truth due to methodological flaws such as poor dose assessment, inadequate controls, confounders, and statistical artifacts. To protect against such false associations, said Hill, it was important to look beyond epidemiology. For instance, any modest positive association, Hill argued, would be much more believable if it was biologically *plausible*. For example, a hypothesis that X-rays causes a type of cancer is inherently more plausible than one that posits which posits that "telepathic signals from aliens on Mars" cause cancer. Moreover, Hill argued, that the cause and effect interpretation of the data should *cohere* with the generally known facts of the natural history and biology of the disease in question. Finally, Hill said that where possible scientists should appeal to *experiment* and try to reveal the true association with the controlled procedures of the laboratory.

### *How Good Is the Epidemiological Evidence?*

How does the epidemiological evidence for power line EMFs and cancer look, when judged against Hill's Criteria? Is it powerful enough by itself to support causation?

As to the criterion of strength, as Table 1 and Table 2 show, the associations are far from strong. The median risk ratio for the residential studies for childhood and adult cancers report small positive risk ratios, hovering around 1.00, and not exceeding 4.00. The occupational studies of workers, which are supposedly exposed to higher EMFs, are, if anything, even weaker, with median risk ratios hovering just above 1.00 and individual study risk ratios rarely exceeding 2.00. These numbers are far below what Hill found with smoking.

As to the next Hill criterion, consistency, a close reading of the individual studies shows they are not especially consistent. While all studies of smoking found lung cancer, not all studies of power lines find the same cancer. Three large occupational studies in the mid 1990s found quite different disease outcomes. Sahl, Kelsh, and Greenland (1993) found no cancers. Thériault et al. (1994) found a small association with leukemia but no link with brain cancer. A study by Savitz and Loomis (1995) found no link with leukemia but a small association with brain cancer. Even for childhood leukemia, the picture is inconsistent. Savitz (1988), using some measures found an association, but Coleman, Bell, Taylor, and Zakelj (1989) did not, and Tomenius (1986) found an inverse correlation—a risk ratio below 1.00—implying EMFs protect against, rather than cause, leukemia.

Finally, the literature shows little or no evidence of a statistically significant dose–response relationship between fields measured using a magnetometer and cancer rates.

As judged by the Hill Criteria then, it appears that epidemiology alone cannot settle the EMF question as it did for smoking and, therefore, power line EMFs may be a more complex and subtle public health issue than Brodeur suggests. Following Hill's suggestion, we pass on to the other Hill criteria: plausibility, biological coherence, and controlled investigation in the laboratory.

### *Living With Reality: The Criterion of Plausibility*

While it may seem reasonable that a large mysterious power line might cause a health effect like cancer, how scientifically *plausible* is this hypothesis? Ironically, it turns out the toxin in question—electromagnetism—is not mysterious at all. In fact, it is one of the best-understood areas in science. In the words of Yale physicist Robert Adair "There's probably nothing . . . in the universe, that we understand as well as electromagnetic fields, and the interaction of electromagnetic fields with matter, including biological matter. All of chemistry and almost all of biology . . . are electrical" (Adair, quoted in Palfreman, 1995, 10:06). As such, the plausibility of the issue depends on long-established laws of classical physics (Bennett, 1994b). Proponents of the EMF-cancer hypothesis, therefore, must deal with a number of "reality constraints."

*Reality Constraint Number One*—Power line fields have very little energy. All electromagnetic radiation travels at the speed of light (in a vacuum), but different types of radiation (for example, X-rays and microwaves) vibrate with different frequencies. Physics says the higher the frequency of an electromagnetic wave, the higher its energy. X-rays, for example, which vibrate some 10 billion, trillion times a second, are energetic enough to break bonds in cellular DNA and directly cause cancer. Lower frequency electromagnetic waves cannot do this. Light waves, for example, lack the energy to break DNA, but can excite electrons and molecules.

Infrared and microwave radiation cannot excite electrons, but it can heat cells and tissues. The even lower frequency EMFs associated with cellular phones, television, FM, and AM radio cannot even heat matter. But they are still much more energetic than power line EMFs.

The extremely low frequency (ELF) electromagnetic fields from power lines vibrate just 60 times a second (in Europe 50 times a second).[6] The physical reality, therefore, is that power line electromagnetic fields are feeble and simply cannot produce cancers in the way that X-rays can by breaking chemical bonds in DNA. Stand under a power line at night during a full moon, for example, and the physical reality is that you will receive a thousand times more electromagnetic energy from moonlight than from the power line. This does not, of course, preclude power line EMFs from causing cancer through some novel, as yet undiscovered, mechanism.

*Reality Constraint Number Two*—Forget about the electric field. Like all electromagnetic radiation, ELF fields have both electric and magnetic components that interact with matter differently. It turns out that electric fields are not penetrating: they are readily shielded by buildings, and do not usually penetrate human skin.[7] Electric fields, therefore, are an implausible candidate as a biological toxin. In contrast, a magnetic field will penetrate just about anything, permeating a human body as if it were free space. Balance a strong magnet on the back of your hand and place the palm over a tray of paper clips. The paper clips leap up trying to reach the magnet. Because magnetic fields penetrate human flesh, and materials from wood to most metals, an early consensus emerged among advocates and skeptics alike that, if power line electromagnetic fields are dangerous, it must be the magnetic field that is doing the damage.

*Reality Constraint Number Three*—Very large magnetic fields are needed to produce perceptible biological effects. Magnetic fields are denominated in units called microTeslas (μT). Very large magnetic fields of 50,000 μT are needed to stimulate excitable tissue such as muscles and nerves. Even stronger fields of 500,000 μT can cause a heart to go into fibrillation. The kinds of magnetic field strengths produced by power lines are much, much smaller than this. The field directly under a 115–765 KV power line right of way (ROW) is typically 10 μT or less. At the edge of the ROW, the magnetic field drops off to 0.1–1 μT. In most residences, magnetic fields are much less still, below 0.02 μT, except near electrical devices (especially those with high speed motors like vacuum cleaners) where, centimeters from the working appliance, they can be intermittently as high as 150 μT. A 2002 analysis of Spanish primary schools, for example, found a median level in classrooms of 0.012 μT and 0.0095 μT in playgrounds (Tardón et al., 2002). This is not only millions of times smaller than the fields that can stimulate nerves but also, according to Yale physicist William Bennett (Bennett, 1994a, 1994b), hundreds of times smaller than the Earth's magnetic field to which we are all exposed 24 hours a day. At around 50 μT the Earth's natural magnetic field dwarfs the typical residential exposure. It also greatly exceeds occupational exposures of linemen and electrical workers. Mean exposures for such workers are around 0.5 to 4 μT (Sahl, Kelsh, Smith, & Aseltine, 1993; Sahl, Kelsh, & Greenland, 1993; Savitz, 1994) with occasional reports of short exposures in excess of 100 μT for arc welders and electrical cable splicers, who use specialized equipment (Kaune, 1993).

Proponents like Brodeur have an answer for Bennett: magnetic fields come in two varieties, static and oscillating. According to Brodeur, stati*c* magnetic fields like the Earth's field are benign, but oscillating ones like those used in AC power lines are a different matter (Brodeur, quoted in Palfreman, 1995, 11.37): "There is absolutely no reasonable biological comparison between the earth's magnetic field . . . and the power frequency fields, [which alternate] to and fro, 60 times a second, to the rhythm of a 60-hertz alternating power. When you're standing underneath a power-line, every cell in your brain and body is entrained to the rhythm."

In other words, unlike a static magnetic field, an oscillating magnetic field will induce an electric current inside the body, and that that current can exert a force on charged ions and, perhaps, through some mechanism cause cancer. But the physicists also have an answer for this.

*Reality Constraint Number Four*—ELF-induced currents are miniscule. The induced currents of power frequency magnetic field—and the forces they exert on moving charges inside the body—can be calculated with precision, and they are not only millions of time too small to break chemical bonds in DNA, they are even thousands of times smaller than the effects of the body's own heat bouncing molecules around. The thermal background noise, in other words, completely drowns out any signal from the power lines (Adair, 1991, 1994). This presents proponents with a serious signal to noise problem.

On April 22, 1995, such arguments led the Council of the American Physical Society (APS) to issue a "Statement on Power-lines and Public Health" on behalf of their 45,000 members saying that fear of power line EMFs was unfounded. It is rare for physicists to play such a proactive role in a public health debate and some proponents questioned their qualifications to participate. But their involvement had altered the parameters of the argument, forcing the proponents to concede the following:

- The toxin is magnetic rather than electrical
- The hypothetical magnetic toxin is an oscillating rather than static.
- The strength of the field is far too small to be genotoxic (i.e., to break chemical bonds directly), but this does not rule out some indirect epigenetic action.
- Before the field could cause disease, it had to be detected, and since the thermal background is 10,000 times larger than the signal from the field, there is a serious signal to noise problem.

While the physicists' knowledge of electromagnetism successfully constrained the debate, it did not settle it; and few epidemiologists, especially those who had devoted decades of study to EMFs, were ready to abandon the field just because the APS told them to. Some proponents even charged them with hubris. As Brodeur put it (Brodeur, quoted in Palfreman, 1995, 16:14): "Who says that the lower frequencies don't operate in another way to cause cancer? Who says that they all have to act in the same way? Who says they do? Ludicrous. I mean, what kind of mind set is that? Well, I fear it's the mindset of the American physicist."

### Can We Get There From Here? The Criterion of Coherence

Moving on to the next Hill Criteria: do the observations cohere with existing biological knowledge of how cancers work? To get from a magnetic field to a disease like cancer there are several links in the chain of evidence. The signal, an induced current from a ELF magnetic field, must (a) be detectable by the human body, (b) cause a biological change, and (c) that change must lead to a disease end point like leukemia or brain cancer. Since the signal is thousands of times smaller than the thermal noise, there logically has to be some filtering hardware mechanism in human beings even to detect the field. Such hardware has been discovered in sharks, which can detect 60 Hz magnetic fields, but not yet in humans. Other scientists (Lednev, 1991; Liboff, 1992) have speculated that there might be a resonant "window" effect whereby human cells are especially responsive to a frequency window that includes 60 Hz. To account for the power systems in Europe (where many studies were carried out), this window must necessarily include 50 Hz as well. Few physicists take such arguments seriously. If sinusoidal power-frequency fields below 5 μT actually do have biological effects, the mechanisms must be found, according to Adair, "outside the scope of conventional physics" (Adair, 1991).

But even if the human body could somehow detect a power line magnetic field, scientists next have to come up with a biological mechanism that can result in a biochemical change in the human body: be it in a molecule, a cell membrane, and so forth, and then explain how this change can go on to produce a disease like cancer. Since the force in the ELF fields is millions of times too small to break chemical bonds and cause cancer directly, it is highly unlikely that ELF fields are "genotoxic," but it is possible that the field acts in an "epigenetic" manner to promote an existing cancer or disease.

Finally, even if a plausible mechanism can be hypothesized that can link exposure and disease, there is the problem of how scientists would prove that the offending fields are power line magnetic fields rather than those from domestic appliances or from electric trains. This latter point—crucial for making policy about ELF fields—is a troubling issue for epidemiologists as well. As UNC, Chapel Hill epidemiologist David Savitz puts it, "if you have someone who's working, let's say, as an electrician . . . if they go home and use an electric blanket, or perhaps live near certain kinds of power-lines, they may actually get an equivalent amount of exposure at home" (Savitz, quoted in Palfreman, 1995, 25:11). In other words, if there is a danger, it is not clear exactly where the greatest danger comes from or which fields should be mitigated.

From the beginning, the issue of exposure measurement had been controversial. Wertheimer and Leeper had not measured magnetic fields directly but had used wire codes as a surrogate. Other epidemiologists had subsequently used magnetometers to measure the fields in residences and the workplace, but some scientists argued that such contemporary spot measurements might not be reliable because they did not capture the historic magnetic fields: the fields that were present possibly years in the past when any cancer might have been acquired. This measurement controversy has continued to plague epidemiological investigation of this issue. Apart from a handful of Scandinavian studies discussed later (Feychting & Ahlbom, 1994) that used an ingenious method to calculate past magnetic fields from utility power line records, epidemiologists have continued to use contemporary measured fields or wire code systems. This has made it difficult for scientists and policymakers to reach consensus on this issue.

### *The Precautionary Principle*

What should policymakers do when presented with a concerned public but inconclusive scientific evidence? One model especially favored in Europe makes use of what has become known as the precautionary principle. According to Kriebel et al. (2001), the term "precautionary principle" came into English as a translation of the German word *Vorsorgeprinzip*, which more accurately is translated as "foresight principle." The principle enshrines a "better safe than sorry" paradigm that seeks to "to ensure that the public good is represented in all decisions made under scientific uncertainty" (Kriebel et al., 2001, p. 7). Where the uncertainty is large, the potential public consequences significant, and the proposed changes relatively inexpensive, the principle is relatively uncontroversial. So, for example, even though there was considerable scientific uncertainty that cell phones interfered with cockpit communications, the public interest was such that it was prudent to err on the side of safety and ban cell phone use in flight.

But is it appropriate to use the precautionary principle for power line EMFs? Some proponents have argued that if there is a credible possibility that power line fields put young children at increased risk for leukemia, then reasonable efforts should be made to mitigate such magnetic fields. On the other hand, opponents counter that because the risk is speculative, mitigating the risk is wasteful, and possibly injurious to the public health. Any benefit of moving school children a mile to another location to avoid a power line magnetic field, for example, would be greatly outweighed by the much larger demonstrable risk of road accidents. Despite the difficulties, some authorities have argued that if reasonable steps can be taken to reduce exposure, then they should be. This was how the Swedish authorities reasoned in 1996 when they recommended the following.

> If measures generally reducing exposure can be taken at reasonable expense and with reasonable consequences in all other respects, an effort should be made to reduce fields radically deviating from what could be deemed normal in the environment concerned. Where new electrical installations and buildings are concerned, efforts should be made already at the planning stage to design and position them in such a way that exposure is limited. (Swedish Occupational Health and Science Administration, 1996)

Another version of the precautionary principle is called prudent avoidance (Nair, Morgan, & Florig, 1989). The doctrine of prudent avoidance argues that if, for a modest cost increase (5% or less), reasonable changes can be implemented that will reduce an alleged toxin, then such changes should be made even before there is solid scientific evidence supporting a causal link. Unfortunately, reducing ELF magnetic fields is likely to be very costly. Because magnetic fields from existing lines and appliances cannot be shielded—except with very expensive nickel-iron alloys, known as mu-metals—the most practical opportunity for ELF magnetic field reduction lies in modifications to new power lines before they are built. But here too the cost can be significant. If, for example, new power lines are buried in pairs rather than hung on cables, then the magnetic fields produced by the cables can be made to cancel out. The downside is that burying lines costs 6 or 7 times as much as hanging the lines on towers.

Policymakers using the doctrines of the precautionary principle and prudent avoidance have to deal with political as well as engineering realities. As Foster has remarked, caution and prudence are double-edged political swords. On the one hand they confer a political benefit—as it looks like action is being taken—on the other hand there is a political risk "of sending the wrong message to the public, that a hazard really exists. (Otherwise why would government recommend taking precautions in the first place?)" (Foster, 2002–2003, p. 12).

Before embarking on expensive and possibly controversial mitigation, policymakers have another precautionary option: to support high-quality scientific research aimed at reducing the scientific uncertainties. This is the course that United States policymakers chose when Congress authorized the EMF-RAPID program.

### *Reducing Uncertainty in the Laboratory: The EMF RAPID Program*

In principle, the best scientific way to determine whether or not ELF EMFs cause cancer would be to randomly assign individuals at birth to one of two teams: one whose members would live their entire lives free from any ELF magnetic fields, the other whose members would be exposed to precisely measured doses, from less than 1 μT to thousands of μT. Each team—which in all other respects would be alike—would then be followed and its health outcomes recorded. Then after 70-odd years scientists would know if the exposed group contracted diseases at a higher rate than the unexposed group. Clearly, there is no way such a human experiment could be mounted, but it is possible (as Hill recommended) to undertake animal versions of such an experiment in the laboratory. Indeed, this was precisely the purpose of a special $65 million federal set-aside to the NIEHS authorized by the 1992 Energy Policy Act.

### *The Criterion of Controlled Animal Experiments*

Imagine a laboratory built entirely from nonmetallic materials, where up to 3,000 rodents can live out their entire 2- to 3-year lifespan under controlled conditions; a place where the temperature, humidity, noise level, light level, food and water are all monitored continuously. Unlike humans in the real world who are constantly exposed to 60 Hz magnetic fields, from overhead and underground cables and domestic appliances, in this lab, the control group of rodents can live out their lives shielded from ELF magnetic fields. By contrast, scientists can expose other groups of rodents to precise doses of magnetic fields: from a few μT to thousands of μT or more. Several such rodent electromagnetic exposure facilities were in fact built and used in the 1990s.

Such facilities allowed investigators to carry out numerous controlled experiments. Several researchers, for example, set out to expose rodents for their entire lives to ELF fields to determine whether those fields are genotoxic. Yasui et al. (1997) exposed male and female rats to 50 Hz magnetic fields at 500 and 5,000 μT and (compared with an unexposed control group) found no increase in cancer incidence, no difference in cancer types (leukemia, lymphoma, brain cancer, and breast cancer) and no difference in mortality. Mandeville et al. (1997) found no difference between female rats exposed to 2 years of 60 Hz fields, at 2, 20, 200, or 2,000 μT, as compared with unexposed controls. McCormick et al. (1999) and Boorman et al. (1999) found that magnetic field exposure had no effect on survival or cancer incidence and found no evidence of any exposure-response trends. This universally negative series of results confirmed what the physicists had said all along: that the fields lacked the energy to break chemical bonds in DNA. Extremely low frequency power line EMFs are not genotoxic.

Scientists were also able to investigate whether ELF EMFs might cause disease by some indirect process; for example, by affecting a cellular process and thereby promoting an existing cancer, or, alternatively, increasing the incidence of reproductive problems, fetal abnormalities, and immunological deficits.

To test the hypothesis that magnetic fields could promote an existing cancer, for example, researchers like Dave McCormick of Illinois Institute of Technology in Chicago used two strains of transgenic mice, genetically engineered to predispose them to lymphoma. For each strain McCormick compared mice exposed to measured amounts of magnetic field with unexposed controls. The result was unambiguous: "We found no evidence that magnetic fields stimulated lymphoma production in either strain . . . the EMF exposure had had no effect" (McCormick, quoted in Palfreman, 1995, 35:57; 1998). This finding was replicated by Harris et al. (1998) and Sommer and Lerchl (2004). Using a different animal cancer model, Ekström, Mild, and Holmberg (1998) and Boorman et al. (1999) found that there was no effect of power frequency fields of 100, 250, or 500 μT on chemically induced breast cancer in rats.[8]

Researchers went beyond cancer to look at other outcomes that had been blamed on EMFs such as fetal abnormalities, reproductive performance, and immune function and failed to demonstrate convincingly any reproducible magnetic field effect, even at doses a thousand times bigger than typical exposures.

The animal data taken together was a serious set back for proponents of an EMF–cancer connection, making expensive policy actions to mitigate fields somewhat less likely. If no effects—no cancers and no abnormalities—could be demonstrated in exposed rodents, even at field strengths of 2,000 μT, it was hardly "prudent" to spend resources reducing residential magnetic fields from 0.02 μT to 0.002 μT. In 1999, the National Academy of Sciences was asked to review the research conducted by NIEHS's EMF RAPID program. In this report, the National Academy of Sciences implied that the matter was now settled. "The results of the EMF-RAPID program do not support the contention that the use of electricity poses a major unrecognized public-health danger . . . The committee recommends that no further special research program focused on possible health effects of power-frequency magnetic fields be funded" (National Research Council, 1999).

### *Hill Criteria be Damned*

Some advocates shrugged off the news from the laboratory as they had the pronouncements of the physicists. Brodeur argued that the EMF-RAPID program results were essentially irrelevant. What really mattered for setting public health policy in his view was not laboratory studies but epidemiology. "Laboratory studies are not going to be the criteria upon which we base preventive public health measures. We have used the epidemiology as the only viable tool for implementing preventive public health measures. It is the only viable tool" (Brodeur, 1995, quoted in Palfreman, 38:55).

For their part, some epidemiologists who had devoted 2 decades of study to this topic, were still reluctant to accept that the scientific question had been completely settled, and argued that the cumulative evidence (London, 1991; Savitz, 1988) suggested a small persistent effect for childhood leukemia. Even the appearance of two large negative epidemiological studies on childhood leukemia (Linet, 1997; McBride et al., 1999) failed to sway this conviction that the balance of studies supported a small association. A divide now opened up between some epidemiologists and other biomedical scientists. So whereas a *New England Journal of Medicine* editorial bluntly concluded that: "18 years of research have produced considerable paranoia, but little insight and no prevention. It is time to stop wasting our research resources" on EMF studies (Campion, 1997, p. 44), Dr. David Savitz of the University of North Carolina insisted more research was still needed. As he put it, ''this doesn't put it to rest'' (Savitz, 1997).

Indeed, two meta-analyses published in 2000 (Ahlbom et al., 2000; Greenland, Sheppard, Kaune, Poole, & Kelsh, 2000) seemed to breathe new life into the controversy. The studies pooled groups of previous studies and reanalyzed them with respect to certain exposure metrics. Both meta-analyses reported an increase in leukemia, but only for the highest exposed groups, with Ahlbom finding a risk ratio of 2 for exposures 0.4 μT and above, and Greenland finding a risk ratio of 1.7 for exposures above 0.3 μT. If these meta-analyses were true, and not explainable in terms of some epidemiological artifact (see below), it would mean that perhaps 1% of leukemia deaths (6 to 8 cases of leukemia) in the United States each year might be attributable to power line fields.

What should policymakers do about such studies, and how does the precautionary principle help them? Policymakers cannot ignore the meta-analyses, but neither can they simply treat them as if they were the only evidence about power lines and cancer. It should be remembered that the power line cancer hypothesis has flunked all of the Hill Criteria: the epidemiology is weak, inconsistent, and lacks a dose response; the hypothesis is physically and biologically implausible; and the controlled animal experiments are universally negative, even at doses vastly higher than typical human exposures. Before enacting expensive mitigation policies, therefore, it behooves scientists and policymakers to scrutinize the methodology being used in these and other positive epidemiological studies. Perhaps the simplest explanation for these recent findings is that they are wrong.

### *The Return of the Texas Sharpshooter*

It is worth revisiting the reasons why Hill argued that weak, inconsistent epidemiology could not be relied on by itself to determine causation. As Hill well understood, there are many factors that can lead epidemiologists to make false associations. Inadequate dose assessment has already been mentioned; unless it is possible to accurately measure magnetic field exposure, then it may be difficult to find an association. Confounders are also a constant worry for epidemiologists. Wertheimer and Leeper's study, for example, some critics claim, failed to control for other (nonmagnetic) factors that also correlate with the wire codes—for example, poverty, traffic density, air pollution, and PCBs. In other words, these factors (rather than EMFs) might have been responsible for any increased cancer incidence. Epidemiologists also need to be cognizant of other possible biases: in, for example, how cases and controls are selected; in which studies get reported; the manner in which studies are published; how completely (or incompletely) studies are reported; the manner in which studies are published; and the spin the mass media puts on those studies.[9] But one other cause of false associations has proved more controversial among epidemiologists and their scientific colleagues: multiple comparisons artifacts.

The concept is best illustrated with a 1994 Swedish study in 1994 (Feychting & Ahlbom, 1994) that went to enormous lengths to measure magnetic dose accurately and to control for confounders and biases. The study was extraordinarily comprehensive (Palfreman, 1996): it looked at 12 different cancer rates (four in children and eight in adults), and used three different methods of calculating magnetic field exposure (measured distances from lines, measured fields using gauss meters, and calculated historic fields using the power company's records[10]). Within each exposure metric there were further subdefinitions (such as different cut-off points for separating "unexposed" from "exposed" from "more exposed" from "most exposed").

By linking many different cancers with many different magnetic field exposures, the team generated "multiple comparisons," in the form of something like 800 risk ratios. And critics remarked that what looks like thoroughness is in fact a fatal methodological flaw. Because the authors have not specified in advance which hypothesis among these hundreds of comparisons they are testing, we must assume they are considering all of them. And the problem is, by considering all possibilities they introduce a lot of statistical noise. By standard statistics, even if nothing is going on, 5% of the 800 risk ratios (30 to 40) would be expected to be statistically elevated above 1.00 (implying EMFs cause a particular form of cancer) and 5% would be below 1.00 (implying that EMFs protect against some cancers). And once the Swedish team had generated so many (noisy) results, it was simply not scientifically valid for them to select only the elevated risk ratios for publication and ignore the rest.[11] The scientific journal made things worse by putting the highest risk ratio in the article's abstract, knowing that the popular media would pick it up. Seen in this context the published associations look far less compelling. The scientific community is left not knowing whether the "significant correlation" of childhood leukemia with calculated historic fields is an indicator of a real association or a piece of statistical noise.

In the same manner, the two above mentioned meta-analyses (Ahlbom et al., 2000; Greenland et al., 2000), which took multiple studies, pooled them and then, *after the fact,* selected cut-points and exposure metrics, also run a serious risk of producing false positive associations due to multiple comparison artifacts. Like the Texas Sharpshooter, these studies do not specify their target in advance; they draw in the target(s) (the exposure metrics, the cut-points, the study subjects) *after* the fact.

While epidemiologists have attempted to defend such data mining (Rothman, 1990; Savitz & Olshan, 1995) other scientists have argued that epidemiologists should avoid such practices or at least correct for post hoc changes in the way they analyze their data sets (Cook & Farewell, 1996). Some physicists have been especially critical of certain epidemiological studies. Richard Wilson, a physicist interested in EMFs, felt compelled to write a letter to the *American Journal of Epidemiology*, suggesting that Feychting and Ahlbom might have fallen into the "Feynman Trap" (Goodstein, 1989; Wilson, 1995), named after the legendary Nobel Laureate Richard P. Feynman. One day, the story goes, Feynman posed a problem for his undergraduate physics students concerning the probability of his seeing a particular unique license plate number as he walked through the car park to the lecture hall. The formal answer is derived by computing the independent probabilities of seeing each number (l/10) and each letter (l/26) in combination and comes out to a very improbable number of around 1 in 18 million. But Feynman was not using this example to test his students' knowledge of probability but rather to make a point about the scientific method. Since Feynman had just seen the license plate on a car (in the parking lot outside the classroom building), his prior knowledge had changed the odds (to 1.00). And since Feynman had asked a question to which he already knew the answer, the statistical calculation was invalid. The Feynman Trap is really another version of the Texas Sharpshooter parable, warning scientists to decide their targets before they start shooting. In the same edition of the journal, Feychting & Ahlbom (1995) seemed to concede this point, claiming they never used the term "statistically significant" in their paper.

### *The End of the Affair?*

Twenty-five years after Wertheimer and Leeper's study, proponents of the power line cancer hypothesis seem to be losing the argument. The hypothesis that ELF EMFs cause adverse health effects has failed all of the Hill Criteria: it lacks physical and biological plausibility; the experimental evidence is strongly negative, and the epidemiology is weak, inconsistent, and nonspecific. Additionally, since the epidemiology is plagued by problems of confounders, exposure definitions, and multiple comparison artifacts, it is likely that any weak positive findings derive from these and other artifacts. Many of the actors—from scientists to lawyers[12]—have moved on.

While some epidemiologists still maintain the issue is not fully resolved, there are signs that most have been impressed by the overwhelmingly negative animal studies. After a long career investigating EMFs, Swedish epidemiologist Anders Ahlbom stated recently that there is no point doing any more epidemiological studies until we know how EMFs can trigger or promote cancer (Ahlbom, quoted in "The Case for EMF Precautionary Policies," 2004).

### *Being Prudent With Prudence*

There are even signs that supporters of the precautionary principle have sought to distance themselves from the EMF issue, lest it undermine the principle's credibility in more important public health battles to come. In November 2002, Mike Repacholi, head of the World Health Organization's EMF Project refused to recommend any action under precautionary principle and warned local health officials from seeking to lower the existing 100 μT limit. A WHO publication (WHO, 2002, p. 57) *Establishing a Dialog on Risks From Electromagnetic Fields,* made the following revealing statement: "If the scientific community concludes that there is no risk from EMF exposure . . . then the appropriate response to public concern should be a public education program." If, on the other hand, it continues, "regulatory authorities react to public pressure by introducing precautionary limits in addition to the already existing science-based limits, they should be aware that this undermines the credibility of the science and the exposure limits."

Likewise, the European Union has increasingly stressed the importance of scientific transparency in using the precautionary principle. As David Byrne, Commissioner for Health and Consumer Protection, remarked in 2001, "If [the precautionary principle] is to become a code or shorthand for blocking or banning everything which is objectionable, its credibility will quickly become lost" (Byrne, 2001).

While some EMF activists remain resolute in their belief that power line EMFs are dangerous, after a 2-decades-long argument, many public health scientists have come to the opposite conclusion: namely, that if these ELF EMFs pose any risks at all, those risks are vanishingly small. The final calculation, therefore, is not risk versus no risk, but cost versus benefit. Given the current state of the science, it makes little public health sense to spend money to lower residential and occupational exposures, especially when doses 100,000 times larger have failed to produce any effect in the laboratory.

The ELF EMF story serves as an important example of how an engaged scientific debate involving multiple perspectives can make real progress and how scientists can, over time, squeeze virtually all of the uncertainty out of a controversy. So while some physical scientists may look back dismissively on this history and argue that it has all been a massive waste of time and money, it can equally well be argued that it is a paradigm case of good science policy in action.

## Notes

1 EMF-RAPID stands for EMF Research and Public Information Dissemination Program.

2 The precautionary principle seeks to implement a "better safe than sorry" approach to science policy. The European Union, for example, states that the principle "may be invoked when the potentially dangerous effects of a phenomenon, product or process have been identified by a scientific and objective evaluation, and this evaluation does not allow the risk to be determined with sufficient certainty." Retrieved September 1, 2005, from http://europa.eu.int/scadplus/leg/en/lvb/l32042.htm.

3 See, for example, reports by National Institute of Environmental Health Sciences (2002), National Institutes of Health (1999), and the National Radiological Protection Board (2004).

4 There are a few exceptions where cluster discoveries have been accepted more or les without question, generally where there is a huge occurrence of an extremely rare disease among a well-defined group of people. In the manufacture of polyvinyl chloride (PVC), workers were exposed to vinyl

chloride monomer (a chemical precursor). Many of these workers contracted angiosarcoma of the liver—a very rare cancer—at a rate some 200 times normal.

5 In the case of smoking, hundreds of studies have reproduced what Doll and Hill found for lung cancer, revealing risk ratios in the range of 10 to 30. See *The health consequences of smoking: A report of the Surgeon General* (2004) at http://www.cdc.gov/tobacco/sgr/sgr_2004/index.htm [retrieved September 1, 2005].

6 At this ultra-low frequency, power lines do not in fact "radiate" any appreciable amount of energy. To make an antenna work very well it has to be about as long as the radiation's wavelength—some 3,000 miles. Consequently, the only energy to be had from a power line is in the "near field," the magnetic fields directly emanating from the current flowing in the line.

7 Electric charges gather on the surface of a conductor. This is why a person inside a metal cage (or a car) survives when the cage/car is hit with lightning; all the charge stays on outer skin of the cage. Even poor conductors shield electric fields (Deno, Zaffanella, & Silva, 1987).

8 These studies were also important because they tried and failed to replicate previous studies by Löscher (1993) and Mevissen (1996).

9 *Publication bias* is the preference of journal editors for positive risk association reports over null findings. Once the popular media have become interested in these reports, two other effects may further enhance the perceived risk. Because journalists are under pressure to tell a story in as simple and dramatic way as possible, they indulge in *sharpening* (using weasel words like "may" and "could" to exaggerate the strength of a finding), and *leveling* (playing down or ignoring the caveats in a report) (Gilovich, 1991; Singer & Endreny, 1993, p. 158).

10 In an ingenious piece of scientific detective work, Feychting and Ahlbom found a way to reconstruct past magnetic fields. Scandinavian electric utility companies have very complete records of line loads going back decades. Using a computer program, the Swedish power company, Vattenfalls, could take these figures for current flowing in their high-voltage transmission lines in past years and calculate the magnetic field at given distances from the wire. Seizing the opportunity, Swedish epidemiologists Feychting and Ahlbom enrolled everyone living within 300 meters of Sweden's high-voltage transmission line system over a 25-year period and used the program to calculate the magnetic fields that the children and adults were exposed to at the time of their cancer diagnosis, and up to 10 years before. While the calculated field does not include exposure from local distribution lines, domestic appliances, the wires in the houses, or from sources outside the home (e.g., trains, underground cables, office appliances), it had captured one part of the historic field.

11 Feychting & Ahlbom can be criticized for being rather selective with their reporting. In the contractor's report, for example, Feychting & Ahlbom compare leukemia rates with calculated magnetic fields at the time of diagnosis, 1 year before diagnosis, 5 years before diagnosis, and 10 years before diagnosis. They find a statistically significant correlation with calculated fields at the time of diagnosis, but not at 1, 5, or 10 years before diagnosis. The authors select only the first for publication, but on what justification? Why is the field at diagnosis better than the field 1 year, 5 years, or 10 years before diagnosis? Cancers generally take several years before they show clinical signs (Palfreman, 1996).

12 It is perhaps not surprising that given the overwhelming biological evidence, personal injury litigation has been unsuccessful. Melissa and Suzanne Bullock of Meadow Street, in Guilford, Connecticut, for example, dropped their suit against Connecticut Light and Power Co. after their expert medical witnesses pulled out.

## About the Author

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## References

Adair, R. K. (1991). Constraints on biological effects of weak extremely-low-frequency electromagnetic fields. *Physical Review A*, *43*, 1039–1048.

Adair, R. K. (1994). Constraints of thermal noise on the effects of weak 60-Hz magnetic fields acting on biological magnetite. *Proceedings of the National Academy of Sciences USA*, *91*, 2925–2929.

Ahlbom, A., Day, N., Feychting, M., Roman, E., Skinner, J., Dockerty, J., et al. (2000). A pooled analysis of magnetic fields and childhood leukaemia, *British Journal of Cancer*, *83*, 692–698.

Bennett W. R. (1994a). Cancer and power lines. *Physics Today*, *47*, 23–29.

Bennett W. R. (1994b). *Health and low-frequency electromagnetic fields*. New Haven, CT: Yale University Press.

Boorman, G. A., McCormick, D. L., Findlay, J. C., Hailey, J. R., Gauger, J. R., Johnson, T. R., et al. (1999). Chronic toxicity/oncogenicity evaluation of 60 Hz (power frequency) magnetic fields in F344/N rats. *Toxicologic Pathology*, *27*, 267–278.

Bradley, E. (Anchor). (January, 1993). *Street stories*. New York: CBS.

Brodeur, P. (1989a). *Currents of death: Power lines, computer terminals, and the attempt to cover up the threat to your health*. New York: Simon and Schuster.

Brodeur, P. (1989b, June 12, 19, & 26). Annals of radiation: The hazards of electromagnetic fields, Parts I, II & III. *The New Yorker*.

Brodeur, P. (1990, July 9). Annals of radiation: Calamity on Meadow Street. *The New Yorker*.

Brodeur, P. (1992, December 7). Annals of radiation: The Cancer at Slater School. *The New Yorker.*

Brodeur P. (1993). *The great power line cover-up: How the utilities and government are trying to hide the cancer hazard posed by electromagnetic fields*. New York: Little-Brown.

Brokaw, T. (Presenter) (1990a, December 13). EMFs. *NBC Evening News*. New York: NBC.

Byrne, D. (2001). *The decision maker's dilemma*. Paper presented at the Joint WHO/FAO.OIE Technical Consultation on BSE. Paris, June 11–14.

Campion, E. W. (1997). Power lines, cancer, and fear. *New England Journal of Medicine*, *337*, 44–46.

Coleman, M. P., Bell, C. M. J., Taylor, H. L., & Zakelj, M. P. (1989). Leukemia and residence near electricity transmission equipment: A case-control study. *British Journal of Cancer 60*, 793–798.

Cook, R. J., & Farewell, V. T. (1996). Multiplicity considerations in the design and analysis of clinical trials. *Journal of the Royal Statistical Society, Series A*, *159*, 93–110.

Deno, D. W., Zaffanella, L. E., Silva, J. M. (1987). Transmission line electric field shielding by objects. *IEEE Transactions of Power Delivery, 2*(1), 269–280.

Ekström, T., Mild, K., & Holmberg, B. (1998). Mammary tumours in Sprague-Dawley rats after initiation with DMBA followed by exposure to 50 Hz electromagnetic fields in a promotional scheme. *Cancer Letters*, *123*, 107–111.

Feychting, M., & Ahlbom, A. (1994). Magnetic fields, leukemia, and central nervous system tumors in Swedish adults residing near high-voltage power lines, *Epidemiology*, *5*, 501–509.

Feychting, M., & Ahlbom, A. (1995). Re "Magnetic fields and cancer in children residing near Swedish high-voltage power lines" Authors' reply [letter]. *American Journal of Epidemiology*, *141*, 378–379.

Foster, K. R. (2002–2003). The precautionary principle: Common sense or environmental extremism. *IEEE Technology and Society Magazine*. Washington, DC: IEEE.

Foster, K. R., Erdreich, L. S., & Moulder, J. E. (1997). Weak electromagnetic fields and cancer, in the context of risk assessment. *Proceedings of the IEEE*, *85*, 733–746.

Gilovich, T. (1991). *How we know what isn't so: The fallibility of human reason in everyday life*. New York: Free Press.

Goodstein, D. L. (1989, February). Richard P. Feynman, teacher. *Physics Today,* 70–75.

Greenland, S., Sheppard, A. R., Kaune, W. T., Poole, C., & Kelsh, M. A. (2000). A pooled analysis of magnetic fields, wirecodes, and childhood leukemia. *Epidemiology*, *11*, 624–634.

Harris, A. W., Basten, A., Gebski, V., Noonan, D., Finnie, J., Bath, M. L., et al. (1998). A test of lymphoma induction by long-term exposure of Eμ-Pim1 transgenic mice to 50-Hz magnetic fields. *Radiation Research*, *149*, 300–307.

Hill, A. B. (1965). The environment and disease: Association or causation? *Proceedings of the Royal Society of Medicine*, *58*, 295–300.

Jennings, P. (Presenter). (1987, November 9). Special assignment power lines/cancer threat. *ABC Evening News*. New York: ABC.

Jennings, P. (Presenter) (1993a, April 6). Swedish EMF study. *ABC Evening News.* New York: ABC.

Jennings, P. (Presenter) (1993b, April 7). Swedish EMF study. *ABC Evening News.* New York: ABC.

Kaune, W. T. (1993). Assessing human exposure to power-frequency electric and magnetic fields. *Environmental Research, 10*(Supplement 4), 121–133.

Koppel, T. (Presenter). (1990, March 9). (Paul Brodeur interview). *Nightline*. New York: ABC.

Kriebel, D., Tickner, J., Epstein, P., Lemons, J., Levins, R., et al. (2001). The precautionary principle in environmental science. *Environmental Health Perspectives, 109*(9), 1–8.

Lednev, V. V. (1991). Possible mechanisms for the influence of weak magnetic fields on biological systems. *Bioelectromagnetics*, *12*, 71–75.

Liboff, A. R. (1992). The "cyclotron resonance" hypothesis: Experimental evidence and theoretical constraints. In B. Norden & K. Ramel (Eds.), *Interaction mechanisms of low-level electromagnetic fields and living systems* (pp. 130–147). Oxford, UK: Oxford University Press.

Linet, M. S., Hatch, E. E., Kleinerman, R. A., Robison, L. L., Kaune, W. T., Friedman, D. R., et al. (1997). Residential exposure to magnetic fields and acute lymphoblastic leukemia in children. *New England Journal of Medicine*, *337*, 1–7.

London, S. J., Thomas, D. C., Bowman, J. D., Sobel, E., Cheng, T. C., & Peters, J. M. (1991). Exposure to residential electric and magnetic fields and risk of childhood leukemia, *American Journal of Epidemiology*, *134*, 923.

Löscher, W., Wahnschaffe, U., Mevissen, M., Lerchl, A., & Stamm, A. (1993). Tumor promotion in a breast cancer model by exposure to a weak alternating magnetic field. *Cancer Letters*, *71*, 75–81, 1993.

Mandeville, R., Franco, E., Sidrac-Ghali, S., Paris-Nadon, L., Rocheleau, N., Mercier, G., et al. (1997). Evaluation of the potential carcinogenicity of 60 Hz linear sinusoidal continuous wave magnetic fields in Fischer F344 rats. *The Federation of American Societies for Experimental Biology Journal*, *11*, 1127–1136.

McBride, M. L., Gallagher, R. P., Theriault, G., Armstrong, B. G., Tamaro, S., et al. (1999). Power-frequency electric and magnetic fields and risk of childhood leukemia in Canada. *American Journal of Epidemiology*, *149*, 831–842.

McCormick, D. L., Boorman, G. A., Findlay, J. C., Hailey, J. R., Johnson, T. R., Gauger, J. R., et al. (1999). Chronic toxicity/oncogenicity evaluation of 60 Hz (power frequency) magnetic fields in B6C3F1 mice. *Toxicologic Pathology*, *27*, 279–285.

McCormick, D. L., Ryan, B. M., Findlay, J. C., Gauger, J. R., Johnson, T. R., Morrissey, R. L., & Boorman, G. A. (1998). Exposure to 60 Hz magnetic fields and risk of lymphoma in PIM transgenic and TSG-p53 (p53 knockout) mice. *Carcinogenesis*, *19*, 1649–1653.

Mevissen, M., Lerchl, A., & Löscher, W. (1996). Study on pineal function and DMBA-induced breast cancer formation in rats during exposure to a 100-mG, 50-HZ magnetic field. *Journal of Toxicology and Environmental Health*, *48*, 169–185.

Moulder, J. E. (2005). *Electromagnetic fields and human health.* An extensive list of frequently asked questions and references. Retrieved September 1, 2005, from http://www.mcw.edu/gcrc/cop/powerlines-cancer-FAQ/toc.html

Moulder, J. E., & Foster, K. R. (1999). Is there a link between exposure to power-frequency electric fields and cancer? *IEEE Engineering in Medicine and Biology Society, 18*(2), 109–116, 1999.

Nair, I., Morgan, M. G., & Florig, H. K. (1989). *Biological effects of power frequency electric and magnetic fields.* Office of Technology Assessment Background Paper. OTA-BP-E53. Washington DC: Government Printing Office.

National Institute of Environmental Health Sciences. (2002). *EMF Questions and Answers.* Retrieved September 1, 2005, from http://www.niehs.nih.gov/emfrapid

National Institutes of Health. (1999). *Health effects from exposure to power-line frequency electric and magnetic fields*. Retrieved September 1, 2005, from http://www.niehs.nih.gov/emfrapid/html/EMF_DIR_RPT/Report_18f.htm

National Radiological Protection Board. (2004). Retrieved September 1, 2005, from_http://www.nrpb.org/publications/documents_of_nrpb/abstracts/absd15–3.htm

National Research Council Committee on the Possible Effects of Electromagnetic Fields on Biologic Systems. (1997). *Possible health effects of exposure to residential electric and magnetic fields.* Washington, DC: National Academies Press.

National Research Council. (1999). Research on power-frequency fields under the Energy Policy Act of 1992. Washington, DC: National Academies Press.

Palfreman, J. (1995). *Frontline: Currents of fear.* [60']. Boston: PBS/WGBH.

Palfreman, J. (1996). Apocalypse not. *Technology Review*, *99*, 24–35.

Rather, D. (Presenter) (1990a, May 21). EMFs *CBS Evening News*. New York: CBS.

Rothman, K. (1990). No adjustments are needed for multiple comparisons. *Epidemiology*, *1*, 43–46.

Sahl, J. D., Kelsh, M. A., & Greenland, S. (1993). Cohort and nested case-control studies of hematopoietic cancers and brain cancer among electric utility workers. *Epidemiology*, *4*, 104–114.

Sahl, J. D., Kelsh, M. A., Smith, R. W., & Aseltine, D. A. (1993). Exposure to 60 Hz magnetic fields in the electric utility work environment. *Bioelectromagnetics*, *15*, 21–32.

Savitz, D. A. (1988). Case-control study of childhood cancer and exposure to 60-Hz magnetic fields. *American Journal of Epidemiology*, *128*, 21–38.

Savitz, D. A. (1997, July 2). Quoted in D. Q. Haney, Associated Press.

Savitz, D. A., & Loomis, D. P. (1995). Magnetic field exposure in relation to leukemia and brain cancer mortality among utility workers. *American Journal of Epidemiology*, *141*, 123–134.

Savitz, D. A., Ohya, T., Loomis, D. P., Senior, R. S., Bracken, T. D., & Howard, R. L. (1994). Correlations among indices of electric and magnetic field exposure in electric utility workers. *Bioelectromagnetics*, *15*, 193–204.

Savitz, D. A., & Olshan, A. F. (1995). Multiple comparisons and related issues in the interpretation of epidemiologic data. *American Journal of Epidemiology*, *142*, 904–908.

Singer, E., & Endreny, P. M. (1993). *Reporting on risk: How the mass media portray accidents, diseases, disasters and other hazards.* New York: Russell Sage.

Sommer, A. M., & Lerchl, A. (2004). The risk of lymphoma in AKR/J mice does not rise with chronic exposure to 50 Hz magnetic fields (1 μT and 100 μT). *Radiation Research*, *162*, 194–200.

Swedish Occupational Health and Science Administration. (1996). Low-frequency electrical and magnetic fields—the precautionary principle for national authorities—guidance for decision-makers. Solna: Swedish Radiation Protection Institute.

Tardón, A.,Velarde, H., Rodriguez, P., Moreno, S., Raton, M., Muñoz, J., et al. (2002). Exposure to extremely low frequency magnetic fields among primary school children in Spain. *Journal of Epidemiology and Community Health*, *56*, 432–433.

Taubes, G. (1995). Epidemiology faces its limits. *Science*, *269*, 164–169.

The case for EMF precautionary policies. (2004, December). *Microwave News*.

Thériault, G., Goldberg, M., Miller, A. B., Armstrong, B., Guéne, L. P., Deadman, J., et al. (1994). Cancer risks associated with occupational exposure to magnetic fields among utility workers in Ontario and Quebec, Canada and France: 1970–1989. *American Journal of Epidemiology*, *139*, 550–572.

Thomas, F. (1994, October 30). EMF fighters stress prudent avoidance. *Omaha World Herald*.

Thomas, F. (1995, January 30). Nebraska group invites power line foe to speak. *Omaha World Herald*.

Tomenius, L. (1986). 50-Hz electromagnetic environment and the incidence of childhood tumors in Stockholm County. *Bioelectromagnetics*, *7*, 191–207.

Wertheimer, N., & Leeper, E. (1979). Electrical wiring configurations and childhood cancer. *American Journal of Epidemiology, 109*(3), 273–284.

Wilson, R. (1995). [Letter]. *American Journal of Epidemiology*, *141*, 378

World Health Organization. (2002). *Establishing a dialog on risks from electromagneticfields*. Retrieved September 1, 2005, from http://www.who.int/peh-emf/publications/EMF_Risk_ALL.pdf

Yasui, M., Kikuchi, T., Ogawa, M., Otaka, Y., Tsuchitani, M., & Iwata, H. (1997). Carcinogenicity test of 50 Hz sinusoidal magnetic field in rats. *Bioelectromagnetics*, *18*, 531–540.