Electromagnetic Field Exposure and Cancer: A Review of Epidemiologic Evidence

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Introduction

The idea that exposure to power-frequency electric and magnetic fields (commonly termed “electromagnetic fields” or EMF) might contribute to human cancer causation has been under close study for nearly two decades. While various hypotheses have been advanced to suggest how such exposure might promote carcinogenesis, the evidence remains inconclusive. Data are of two kinds: (1) epidemiologic observations concerning the occurrence of childhood and adult cancers under different residential and occupational exposure conditions and (2) experimental studies seeking reproducible evidence of carcinogenic effects arising from EMF exposure in cells, tissues, and laboratory animals.

To date, no form of electromagnetic energy at frequency levels below those of ionizing radiation (x-rays) and ultraviolet radiation has been shown to cause cancer. Nonetheless, public interest has been widespread and continuous because of the ubiquitous presence of electric power in modern society and because of our reliance on technologies that generate higher frequencies of non-ionizing radiation (radio, television, microwaves). It is important, therefore, for societal as well as scientific reasons, to explore questions of biologic effect and possible human health impairment and, in particular, to test all reasonable hypotheses regarding potential carcinogenicity.

Early observations concerning cancer and EMF exposure came independently from two lines of epidemiologic inquiry, one concerning potential occupational exposures and the other residential. The initial occupational study to appear in the medical literature was a proportional mortality analysis that suggested that risk of leukemia was increased for persons who worked in electrical trades.1 The earliest residential study also focused on leukemia and compared children with and without that disease with respect to potential EMF exposure in home settings.2 Exposure was assessed indirectly by observing configurations of power-line wiring outside the children’s homes. Hypotheses have subsequently been proposed by which such postulated occupational and residential exposures might contribute to carcinogenesis. Ongoing experimental studies testing these hypotheses, however, have yet to confirm them through reproducible observations. In the meantime, numerous epidemiologic studies of diverse sorts have addressed the topic. None has yet provided fully persuasive results, and all have been hampered
to one degree or another by limited ability to define and measure biologically relevant EMF exposure.3-7 This article provides an updated survey of epidemiologic information and considers those data in relation to the many scientific uncertainties that still persist.

**Electric and Magnetic Fields**

Power-frequency fields arise whenever alternating current flows in electric power circuits. Such fields have a wave frequency of 50 to 60 oscillations per second (50 to 60 Hz) and are associated with long wavelengths (over 5,000 km) and low quantum energy. These levels of frequency, wavelength, and energy exist near the low end of the electromagnetic spectrum within the extremely low frequency or ELF band (Figure). The term “electromagnetic field” is generally used rather than “electromagnetic radiation” whenever wavelengths greatly exceed distances from exposure sources.

Whenever current flows, both electric and magnetic fields arise. The strength or intensity of electric fields is proportional to the force of flow (voltage), while the strength of magnetic fields is proportional to the rate of flow (amperage). Electric fields are measured in volts per meter and magnetic fields in amperes per meter, or more conventionally as units of magnetic flux density (gauss or tesla; 1 tesla = 10,000 gauss).

The intensity of both electric and magnetic fields falls sharply with distance from electric current circuits or from power sources. Because voltage determines the intensity of electric fields, high-voltage transmission and primary-distribution power lines are the major sources of electric field exposure in both occupational and residential settings. In contrast, magnetic field exposures are most intense where high currents exist, for instance, occupational exposure to arc welding or induction heating and residential exposure to electrical appliances. In practice, the measurement of exposure to power-frequency fields is complex because of interactions among coexisting fields that may arise simultaneously from diverse sources, including static geomagnetic fields. Electric fields are mostly blocked by intervening grounded objects, while magnetic fields move easily through most materials, including tissue. Because of this ability to penetrate tissues, magnetic fields are the principal focus for most studies regarding carcinogenesis.

**Possible Biologic Activity**

The possible action of EMF on biologic tissue has been postulated to involve an ability, through magnetic induction, to stimulate secondary electric currents at cell membranes and in tissue fluids. Although these currents are much weaker than those that exist normally in cells and tissues, various mechanisms have been
suggested by which they might produce cell changes that in turn might serve to promote different phases of carcinogenesis. While no consistent experimental data have yet appeared to establish such mechanisms, despite much research attention, several theoretical possibilities have been advanced. It again deserves emphasis, of course, that EMF, like all forms of non-ionizing radiation, other than the higher frequencies of ultraviolet radiation, does not possess sufficient energy to disrupt molecular bonds (i.e., to cause ionization) and hence is not capable of causing mutations or initiating carcinogenesis by that means.

Proposed theories of biologic action suggest that EMF may serve either to amplify normal electric currents in tissues and cells or affect those currents through resonance with local field forces. Such action is postulated to transfer kinetic energy to ionic flow at cell membranes, perhaps calcium ion flux in particular, with effective transfer being perhaps dependent on specific “windows” of frequency and amplitude. It has been further suggested that such energy transfers may ultimately affect particular cellular enzyme systems (ornithine decarboxylase, for instance) that might influence cell proliferation and perhaps transcription of DNA.

Particular attention has been given to the concept that EMF exposure may also suppress pineal gland production of melatonin, thereby promoting the occurrence of cancers, especially breast cancer. This theory arises from knowledge that EMF can influence circadian rhythms in experimental animals and that patterns of melatonin secretion rise and fall with normal day-night cycles of visible light exposure. Some animal experiments have suggested increases in the frequency of breast cancer associated with suppression of melatonin secretion after exposure to EMF. Although these experimental observations have not been fully confirmed, the theory has directed epidemiologic attention to seeking a possible relationship between EMF exposure and risk for human breast cancer.

### Residential Studies

Following the initial 1979 report, 13 epidemiologic studies have been published concerning residential EMF exposure and cancer risk. Five have been from the United States (two from the Denver area where the initial study was conducted), four from Great Britain, and four from Scandinavian countries. The general results of all studies are summarized in Table 1, with emphasis on the two cancer sites that have received the greatest research attention (leukemia and brain cancer). In many instances, other sites were also studied, separately (especially lymphoma) or in the aggregate.

Adult cancers were examined in five of the 13 studies. The earliest study examined all cancers together and described a significant increase of 39 percent in risk as judged by wiring configurations. The other four focused on leukemia and found no statistically significant increases in risk. Ten studies examined cancer risks in children and teenagers. EMF exposure was assessed either by indirect means (grading configurations of wiring near residences or measuring distances from high-voltage transmission lines or electrical substations, with secondary estimation of magnetic field strength in some instances) or by direct measurement of magnetic fields in homes.

Childhood cancer findings have varied both with respect to risk values for the same cancer site and with respect to methods of exposure assessment. Aside from the initial study in which significantly increased risk was seen for all sites examined, only four of the ten subsequent studies found significant increases in risk: two for brain cancer and for all sites combined and two for leukemia. Three of these four studies compared two different methods for estimating EMF expo-
### Table 1
Epidemiologic Observations Concerning Risks of Cancer and Residential Exposure to Electric and Magnetic Fields

| Reference (Year)                      | Study Type, Location, Time Period | Age of Cases (Years) | Method of Assessing Exposure | Type of Cancer | Number of Cases | Estimate of Relative Risk |
|---------------------------------------|-----------------------------------|----------------------|-----------------------------|----------------|-----------------|--------------------------|
| Wertheimer and Leeper² (1979)         | Case-control, Denver area, 1950-73| 0-18                 | Wiring configuration        | All cancer     | 328             | 2.23*                    |
|                                       |                                   |                      |                             | Leukemia       | 155             | 2.98*                    |
|                                       |                                   |                      |                             | Brain          | 66              | 2.40*                    |
| Leeper² (1979)                        | Denver area, configuration        |                      |                             |                |                 |                          |
| Fulton et al⁸ (1980)                  | Case-control, Rhode Island, 1964-78| 0-20                 | Wiring configuration        | Leukemia       | 119             | 1.08                     |
|                                       |                                   |                      |                             |                |                 |                          |
| Wertheimer and Leeper⁹ (1982)         | Case-control, Denver area, 1967-75| 19+                  | Wiring configuration        | All cancer     | 1,179           | 1.39*                    |
|                                       |                                   |                      |                             |                |                 |                          |
| Tomenius¹⁰ (1986)                     | Case-control, Stockholm, Sweden, 1958-73| 0-18               | Field measurement (≥0.3 μT) | All cancer     | 1,129           | 2.1*                     |
|                                       |                                   |                      |                             | Leukemia       | 243             | 0.3                      |
|                                       |                                   |                      |                             | Brain          | 294             | 3.7*                     |
| McDowell¹¹ (1986)                    | Cohort, East Anglia, UK, 1971-73  | All ages             | Nearness to field source (≤14 m) | All cancer | 213             | 1.03                     |
|                                       |                                   |                      |                             | Leukemia       | 6               | 1.43                     |
| Savitz et al¹² (1988)                | Case-control, Denver area, 1976-83| 0-14                 | Wiring configuration        | All cancer     | 320             | 1.53*                    |
|                                       |                                   |                      |                             | Leukemia       | 97              | 1.54                     |
|                                       |                                   |                      |                             | Brain          | 59              | 2.04*                    |
|                                       |                                   |                      | Field measurement (≥2.0 mG) | All cancer     | 128             | 1.35                     |
|                                       |                                   |                      |                             | Leukemia       | 36              | 1.93                     |
|                                       |                                   |                      |                             | Brain          | 25              | 1.04                     |
| Severson et al¹³ (1988)              | Case-control, Seattle area, 1981-84| 20-79                | Wiring configuration        | ANLL           | 97              | 0.84                     |
|                                       |                                   |                      |                             |                |                 |                          |
| Coleman et al¹⁴ (1989)                | Case-control, London area, UK, 1965-80| All ages | Nearness to field source (≤50 m) | Leukemia (age 0-17) | 84              | 1.5                      |
|                                       |                                   |                      |                             | Leukemia (age 18+) | 687             | 2.0                      |

*95 percent confidence interval excludes 1.00
ANLL = acute nonlymphocytic leukemia
| Reference (Year) | Study Type, Location, Time Period | Age of Cases (Years) | Method of Assessing Exposure | Type of Cancer | Number of Cases | Estimate of Relative Risk |
|------------------|----------------------------------|----------------------|-----------------------------|----------------|----------------|--------------------------|
| Myers et al\(^1\)\(^5\) (1990) | Case-control, Yorkshire area, UK, 1970-79 | 0-14 | Nearness to field source (≤100 m) | All cancer | 374 | 1.04 |
| London et al\(^1\)\(^6\) (1991) | Case-control, Los Angeles County, 1980-87 | 0-9 | Wiring configuration | Leukemia | 211 | 2.15* |
| Youngson et al\(^1\)\(^7\) (1991) | Case-control, Yorkshire area, UK, 1983-85 | 15+ | Nearness to field source (≤50 m) | Hematologic cancer | 3,144 | 1.29 |
| Olsen et al\(^1\)\(^8\) (1993) | Case-control, Denmark, 1968-86 | 0-14 | Field calculated from source (≥0.1 μT) | All cancer | 1,707 | 1.4 |
| Fechtling and Ahlborn\(^1\)\(^9\) (1993) | Case-control, Sweden, 1960-85 | 0-15 | Nearness to field source (≤50 m) | All cancer | 141 | 1.0 |
| Verkasalo et al\(^1\)\(^0\) (1993) | Cohort, Finland, 1970-89 | 0-19 | Field calculated from source (≥0.3 μT) | All cancer | 140 | 1.5 |

*95 percent confidence interval excludes 1.00.
ANLL = acute nonlymphocytic leukemia
Two found significant increases in risk only with the wiring configuration method and not with direct field measurements,\textsuperscript{12,16} and the other found a significant increase in leukemia risk when judged by nearness to field source but not by actual field measurement.\textsuperscript{19} A significant tendency for risk to increase with increasing measure of exposure was present in both of the studies that were positive for leukemia,\textsuperscript{16,19} but not in the other two.\textsuperscript{10,12}

Two further analyses have combined the results of individual investigations of childhood cancers in order to increase statistical power. One combined eight sets of data and compared three different methods for assessing EMF (Table 2).\textsuperscript{3} Results found significantly increased risk (1) for leukemia, brain cancer, and all cancer combined using wiring configuration methods and (2) for all cancer combined and all cancer other than leukemia and brain cancer using direct field measurement, but no significant risk increases when exposure was judged entirely by nearness to field source.

In the second combined analysis,\textsuperscript{21} 13 studies were entered into a meta-analysis that found significant risk increases for leukemia (relative risk, 1.49) and brain cancer (relative risk, 1.89) but not for lymphoma. Methods for assessing EMF exposure were grouped, and individual studies were rated for strengths and weaknesses of epidemiologic methodology and design. No relationship was seen between such indicators and values of relative risk.

### Household Appliances

Another aspect of residential EMF exposure is the possible contribution of fields generated by household appliances. Because the intensity of magnetic fields is greatest close to appliances in use, particular epidemiologic attention has been given to appliances that involve especially close personal contact (electric blankets, razors, etc.). Eight studies have published data in this regard (Table 3).\textsuperscript{13,16,22-27} Electric blanket use was studied in seven instances\textsuperscript{13,16,22-25,27} and other appliance

| Type of Cancer | Nearness to Field Source | Wiring Configuration | Field Measurement |
|----------------|--------------------------|----------------------|-------------------|
|                | OR 95% CI                 | OR 95% CI            | OR 95% CI         |
| All cancer     | 1.11 0.71-1.73            | 1.52 1.04-2.25       | 1.82 1.09-3.04    |
| Leukemia       | 1.35 0.73-2.48            | 1.39 1.08-1.78       | 1.16 0.65-2.08    |
| Brain          | 3.96 1.00-15              | 2.04 1.11-3.76       | 1.85 0.91-3.77    |
| Other cancer   | 0.99 0.55-1.78            | 1.37 0.84-2.23       | 2.96 1.30-6.72    |

*Estimates of risk using different measures of exposure, pooled observations from eight case-control studies (1979-1991).\textsuperscript{3}

OR = odds ratio; CI = confidence interval
### Table 3
Case-Control Observations on Risks of Cancer and Exposure to Electric and Magnetic Fields From Household Appliances

| Reference          | Study Location and Time Period | Age of Cases (Years) | Appliance                          | Type of Cancer          | Number of Cases | Estimate of Relative Risk |
|--------------------|--------------------------------|----------------------|------------------------------------|-------------------------|-----------------|---------------------------|
| Preston-Martin et al\(^{22}\) (1988) | Los Angeles County, 1979-85 | 20-69                | Electric blanket                   | AML                     | 116             | 0.9                       |
|                    |                                |                      |                                    | CML                     | 108             | 0.8                       |
| Severson et al\(^{13}\) (1988)     | Seattle area, 1981-84          | 20-79                | Electric blanket                   | ANLL                    | 114             | 2.40                      |
| Savitz et al\(^{23}\) (1990)        | Denver area, 1976-83           | 0-14                 | Electric blanket                   | All cancer              | 244             | 1.5                       |
|                    |                                |                      |                                    | Leukemia                | 73              | 1.5                       |
|                    |                                |                      |                                    | Brain                   | 47              | 1.2                       |
|                    |                                |                      | Electric blanket                   | All cancer              | 233             | 1.3                       |
|                    |                                |                      |                                    | Leukemia                | 70              | 1.7                       |
|                    |                                |                      |                                    | Brain                   | 45              | 2.5*                      |
|                    |                                |                      | Heated water bed, bedside electric clock, hair dryer | No significant increases in cancer risk at any site |                    | |
| Verrault et al\(^{24}\) (1990)     | Seattle area, 1981-84          | 20-69                | Electric blanket                   | Testicular              | 182             | 1.0                       |
| Vena et al\(^{25}\) (1991)          | Buffalo area, 1987-89          | 41-85                | Electric blanket                   | Breast (postmenopausal) | 382             | 0.89                      |
| London et al\(^{16}\) (1991)        | Los Angeles County, 1980-87    | 0-9                  | Electric blanket                   | Leukemia                | 232             | 1.21                      |
|                    |                                |                      | Hair dryer                         | Leukemia                | 232             | 2.82*                     |
|                    |                                |                      | Black/white television             | Leukemia                | 232             | 1.49*                     |
|                      |                                |                      | Other appliance use (4 prenatal, 11 postnatal) | No significant increases in leukemia risk |                    | |
| Lovely et al\(^{26}\) (1994)       | Seattle area, 1981-84          | 20-79                | Electric razor                     | ANLL                    | 110             | 1.33                      |
|                    |                                |                      | Hair dryer                         | ANLL                    | 102             | 0.38*                     |
|                    |                                |                      | Massage unit                       | ANLL                    | 111             | 3.00*                     |
| Vena et al\(^{27}\) (1994)          | Buffalo area, 1986-91          | 40-49                | Electric blanket                   | Breast (premenopausal)  | 290             | 1.18                      |

*95 percent confidence interval excludes 1.00.

AML = acute myelocytic leukemia; CML = chronic myelocytic leukemia; ANLL = acute nonlymphocytic leukemia
use (hair dryer, electric razor, etc.) in
three.16,23,26 Six studies concerned cancer in adults13,22,24-27 and two in children.16,23
Only one study examined risk at multiple
cancer sites.23 Of the others, four studied
leukemia,13,16,22,26 two breast cancer,25,27
and one testicular cancer.24
Results have been largely negative.
Electric blanket use was not associated
with excess risk except in one childhood
cancer study where risk of brain cancer
was increased in relation to maternal use
during pregnancy.23 In the other child-
hood study, risk of leukemia was in-
creased with hair dryer use and with the
presence of black and white television in
the child’s bedroom.16 In one study of
adult acute leukemia, risk was signifi-
cantly increased with use of electrical
massage equipment but significantly de-
creased for hair dryer use.26 In no in-
stance was there persuasive evidence
that risk might increase with greater fre-
quency or duration of use.

**Occupational Studies**
A large number of epidemiologic studies
have now been conducted concerning
EMF exposure in occupational settings
and their possible influence on risk of
cancer. Several reviews of this work have
found relatively little evidence for consis-
tent links between EMF and particular
cancers,3,5,28-30 although some data have
supported possible relationships with
leukemia and brain cancer. Table 4 con-
tains a summary of information adapted
from the most recent review in which esti-
mates of risk were pooled from 17 studies
that were published through 1990 and
that used a variety of different method-
ologic approaches.3 The pooled data
showed modest increases in risk for can-
cers as a whole, as well as for leukemia
and brain cancer. However, none of these
risk increases were statistically significant
except for a rise of 23 percent in brain
cancer risk among welders. Special atten-

**Table 4**
Cancer and Occupational Exposure to Electric
and Magnetic Fields

| Study Design | Occupational Groups | Type of Cancer | Number of Cases | Estimate of Relative Risk |
|--------------|---------------------|----------------|-----------------|--------------------------|
| Diverse     | Welders             | Leukemia       | 187             | 0.94                     |
|              |                     | Brain          | 178             | 1.23                     |
| Mortality statistics, UK | Electrical workers | Leukemia       | 138             | 1.24                     |
|              |                     | Brain          | 175             | 1.19                     |
|              |                     | Other cancer   | 4,014           | 1.18                     |
| Proportional mortality | Electrical workers | Leukemia       | 495             | 1.14                     |
|              |                     | Brain          | 153             | 1.23                     |
|              |                     | Other cancer   | 2,402           | 1.04                     |

*Estimates of risk for selected occupational groups and different study designs (17 studies, 1979-90).3
†95 percent confidence interval excludes 1.00.
tion has been given to occupations involving welding because of the relative intensity of EMF exposure that such workers may experience. Despite such exposure, evidence of any increased cancer risk is weak, if not negative.29

Fourteen further epidemiologic studies regarding cancer and occupational EMF exposures have been published since 1990,31-44 some more comprehensive in their design and extensive in their assessment of EMF exposure than others (Table 5). Half have been from the United States,32,36,37,39,42-44 one from France,24 one from France and Canada,41 and the remainder from Scandinavian countries.31,33,35,38,40 Nine studied a variety of job categories associated with EMF exposure,31-35,38,39,42,43 three studied workers at electric utilities,37,41,44 and one each studied telephone linemen36 and railway workers.40 EMF exposure was judged at least partially in seven studies by measuring field strengths in the workplace35-37,39-41,44 and by coding job descriptions in the remainder. Five studies examined data for all cancer sites,33,37,38,41,44 three were restricted to two sites (leukemia and brain cancer),31,35,40 and six to single sites, three leukemia34,36,39 and three breast cancer.32,42,43 In all, 11 studies analyzed risk patterns for leukemia, eight for brain, and five for breast, as cancer sites of particular interest.

Findings have been diverse, without clear or strong disease patterns or exposure relationships. Eight of the 11 studies that examined leukemia found some degree of statistically significant elevation of risk, and in five there was at least a suggestion that risk might be greater under longer or more intense exposure conditions.32,33,35,36,44 Of the eight investigations that studied brain cancer, four found some increase in risk, three with a possible relationship to extent of exposure.33,35,44 The five studies of breast cancer included three involving men only,32,33,43 one women only,42 and one both sexes.38 The female breast cancer analysis showed a significant rise in EMF-related risk but without evidence of increasing risk with increasing exposure. Of the three male-only studies, breast cancer risk was increased in two, with evidence in each of some greater risk with greater exposure.32,33 Overall, increased risk values at particular cancer sites ranged from about 1.5 to 6.0, the highest values occurring where numbers of cases were smallest and hence statistical confidence bounds were widest.

Paternal Occupation

Interest in the potential role of environmental factors in the causation of childhood cancer has led to studies measuring cancer risk in relation to paternal occupation. Six such studies have focused on occupations involving EMF exposure,45-50 especially with respect to brain cancer (Table 6). Three of these studies have concerned cases of neuroblastoma in particular.45,49,50 Information on exposure was limited to paternal occupations, with emphasis on occupations at the time of children’s birth (information on maternal occupations was generally too scanty to permit analysis). Cases were identified through cancer registry records in three instances46,49,50 and through review of death certificate diagnoses in the remainder. Occupational data were obtained from birth certificates in four instances45,47-49 and by maternal interview in two.46,50

Two of the three studies that examined brain cancers as a whole described significant risk increases related to EMF exposure in particular occupational categories.47,48 In one instance the risk increase was seen for paternal occupations involving assembly, installation, and repair of electrical equipment,47 and in the other the occupational category was electrician.48 Risk was based on analysis of 19 cases in the first study and six in the second. Of the three neuroblastoma studies, only one found evi-
# Table 5

Epidemiologic Observations Concerning Risks of Cancer and Occupational Exposure to Electric and Magnetic Fields

| Reference (Year) | Study Type, Location, Time Period | Trade Categories | Type of Cancer | Number of Cases | Assessment of Increased Risk* |
|------------------|-----------------------------------|------------------|----------------|----------------|-------------------------------|
| Tornquist et al\(^{31}\) (1991) | Cohort, Sweden, 1961-79 | 35 jobs with possible EMF exposure by job description | Leukemia | 334/250 | 7 instances of increased risk ranging from 1.5 (glioblastoma) to 5.7 (AML), each in a different job category with no clear patterns. |
| Demers et al\(^{32}\) (1991) | Case-control, USA, 1983-87 | 4 job groupings, with different levels of possible EMF exposure by job description | Breast (men) | 33 | 1.8 for all job categories combined, 6.0 for electrical trades (13 cases). Risk greatest after 30 years and for young age at first employment. |
| Tynes et al\(^{33}\) (1992) | Cohort, Norway, 1961-85 | 12 jobs, with possible EMF exposure by job description | All cancer | 3,806/12/107/119 | For all trades, 1.06 all cancers, 2.07 breast, 1.41 leukemia (3.18 TV repair, 1.90 power-line workers), 2.20 brain (railway track walkers). Risk greatest with 10+ years employment. |
| Richardson et al\(^{34}\) (1992) | Case-control, France, 1984-88 | All workers, with industrial hygiene grading for EMF exposure | Acute leukemia | 14 | 3.9 for EMF exposures other than arc welding. Three cases in electronic engineers. |
| Floderus et al\(^{35}\) (1993) | Case-control, Sweden, 1983-87 | All workers, with worksite EMF measurement | Leukemia | 250/261 | 3.0 for CLL at highest EMF quartile, risk increasing with exposure. 2.1 for astrocytoma at highest EMF decile. |

*For all relative risk values cited, 95 percent confidence intervals exclude 1.00.

CLL = chronic lymphocytic leukemia; ANLL = acute nonlymphocytic leukemia; CML = chronic myelocytic leukemia; AML = acute myelocytic leukemia
## Table 5 (Continued)
Epidemiologic Observations Concerning Risks of Cancer and Occupational Exposure to Electric and Magnetic Fields

| Reference (Year) | Study Type, Location, Time Period | Trade Categories | Type of Cancer | Number of Cases | Assessment of Increased Risk* |
|------------------|-----------------------------------|------------------|----------------|----------------|------------------------------|
| Matanoski et al36 (1993) | Case-control, New York, 1975-80 | Telephone linemen, with industrial hygiene grading for EMF exposure and some EMF field measurement | Leukemia (except CLL) | 124 | No significant risk increases. Suggestive rise in risk with increasing exposure. |
| Sahl et al37 (1993) | Cohort and case-control, Southern California, 1960-88 | Electric utility workers, sampled for EMF measurements | All cancer | 496 | No significant risk increases or rising risks with increasing exposure. |
| Guénel et al38 (1993) | Cohort, Denmark, 1970-87 | All workers, with coding for continuous EMF exposure (men and women) | All cancer | 1,056 | 1.64 for leukemia in men (mostly electricians and foundry workers). No significant increases at other sites for either sex. |
| London et al39 (1994) | Case-control, Los Angeles County, 1972-90 | Electrical workers with worksite EMF measurements | All leukemia | 121 | 1.3 for all cases, 2.3 for CML with measured EMF. |
| Tynes et al40 (1994) | Case-control, Norway, 1958-90 | Railway workers historical and measured estimates of EMF exposure | Leukemia | 52 | No increased risks comparing electrical and nonelectrical railway workers, and no increasing risk with greater EMF exposure. |
| Thériault et al41 (1994) | Case-control, Quebec, Ontario, France, 1970-89 | Workers at three electric utilities, EMF exposure measured in sample of current workers | All cancer | 4,151 | 2.41 for ANLL and 3.15 for AML. No increased risk for 23 other cancer sites. No relation to dose. No consistency among the three utilities studied. |

*For all relative risk values cited, 95 percent confidence intervals exclude 1.00.

CLL = chronic lymphocytic leukemia; ANLL = acute nonlymphocytic leukemia; CML = chronic myelocytic leukemia; AML = acute myelocytic leukemia.
dence of significantly increased risk. This involved 17 cases in which paternal occupation included a broad range of electrical trades (electrician, lineman, utility worker, welder, and electrical equipment sales and repair) (17 cases) and six cases where paternal occupation was “electronic worker.” In all instances where increased risk of childhood brain cancer was suggested in relation to paternal occupational EMF exposure, numbers of cases were relatively small and no ancillary data were at hand to judge the relationship of potential risk to extent or duration of exposure.

**Discussion**

Evidence suggesting that exposure to EMF may or may not promote human carcinogenesis is mostly based on the epidemiologic observations reviewed above. While those observations may suggest...
such a relationship for leukemia and brain cancer in particular, the findings are weak, inconsistent, and inconclusive. This perplexing state of affairs reflects several aspects both of the epidemiologic data themselves and of the total range of currently available research information.

Where published studies show increased values of risk, those increases are not great, the larger increases tending to arise from small numbers with relatively wide statistical confidence intervals. Those occasional risk patterns that suggest rising risk with rising levels of exposure (biologic gradient or dose-response) are inconsistent and not often repeated in

| Reference (Year) | Study location and time period | Ages of Cases | Type of Cancer | Number of Cases | Increased Risk* with Paternal EMF Occupation at Birth or Preconception |
|------------------|-------------------------------|---------------|----------------|----------------|-----------------------------------------------------------------------|
| Spitz and Johnson (1985) | Texas, 1964-78 | 0-14 | Neuroblastoma | 157 | 2.13 for electrical workers (17 cases), 11.75 for electronic workers only (6 cases). |
| Nasca et al (1988) | New York State, 1968-77 | 0-14 | Brain | 338 | No significant increases for electrical workers variously defined (15-19 cases). |
| Wilkins and Koutras (1988) | Ohio, 1959-78 | 0-19 | Brain | 491 | 2.4-3.6 for electrical workers variously defined (16-19 cases) |
| Johnson and Spitz (1989) | Texas, 1964-80 | 0-14 | Brain | 499 | 3.52 for electricians (7 cases). No significant increase for EMF-exposed trades overall (25 cases). |
| Wilkins and Hundley (1990) | Ohio, 1959-78 | 0-15 | Neuroblastoma | 101 | No significant increases for electrical workers variously defined (4-24 cases). |
| Bunin et al (1990) | Delaware area, 1970-79 | Children | Neuroblastoma | 104 | No significant increases for electrical workers variously defined (9-14 cases). |

* For all values of relative risk cited, 95% confidence intervals exclude 1.00.
different studies. Increases in risk at specific cancer sites are likewise inconsistent. While some studies suggest increased risk for both leukemia and brain cancer, others do so for leukemia but not brain cancer and vice versa. Where breast cancer has been studied, results also vary. Such inconsistencies persist even when one limits attention to larger, stronger studies (discounting the initial investigations that serve principally to raise hypotheses for later inquiry). In an effort to understand such suggestive but inconclusive and inconsistent epidemiologic results, matters of study design and analytic approach have received considerable scrutiny. Such matters include comparability of cases and controls and the degree to which competing risk factors are managed in analysis. In this regard, it should be emphasized that when studies of residential exposure were compared, no correlation was found between positive results and strengths of epidemiologic methodology.

Much attention has also been given to the uncertainties that accompany any of the several measures thus far used for assessing EMF exposure. Logically, direct field measurement should be the most accurate approach, preferably made using personal monitoring devices in locations where exposure would be greatest. To date, such measurements, in both case-control and retrospective cohort studies, have been necessarily made after the time of case diagnosis and hence can only be used to estimate what conditions of EMF exposure might have been experienced some years earlier when cancer was developing, if exposure conditions have remained unchanged. It is apparent, however, from two well-designed studies of childhood cancer risk in relation to residential exposure that the exposure surrogate of wiring configurations is more strongly associated with heightened risk than direct-field measurement after case occurrence. This observation suggests either that wiring configurations are merely associated with cancer risk factors not related to EMF (suggestions have included chemical exposures from greater nearby density of motor vehicle traffic and increased local opportunities for childhood viral infections) or that wire codes are in fact a better reflection of long-term EMF exposure patterns than measurements obtained after cancer diagnosis. The main avenue for resolving this dilemma would seem to lie with more relevant field measurements of EMF closer in time to cancer promotion and hopefully based on improved basic understanding of the biologic activity of EMF. To date, however, research has yet to confirm or extend any of the several hypotheses that have been advanced as possible carcinogenic mechanisms.

It has been suggested that one test of the idea that EMF exposure may increase risk of cancer should be whether the great growth in society’s use of electricity in this century can be correlated with significant rises in cancer occurrence. Because there is little evidence of such correlation, particularly with respect to specific forms of childhood cancer, one might conclude, on that ground alone, that no significant link may exist between EMF exposure and cancer. However, despite progressive community electrification, it seems unlikely that average residential exposures have increased appreciably, partly because wiring installation practices have changed and because changes have likely occurred in the distribution of other potential cancer risk factors.

The weakness and inconsistent nature of epidemiologic data, combined with the continued dearth of coherent and reproducible findings from experimental laboratory research, leave one uncertain and rather doubtful that any real biologic link exists between EMF exposure and carcinogenicity. In the meantime, while considerable research funding...
is being devoted to the study of potential links, very real economic effects are being felt. Public concern has led to costly litigation, to delays or changes in the installation and operation of electrical transmission equipment, and to a tendency for property values to decrease at locations adjoining high-voltage transmission lines. Should our research investment not lead to reproducible and cohesive results, the scientific community will need to reach some consensus about the likelihood and possible extent of risk. While it may continue to be impossible to prove either the presence or absence of risk, perhaps it can be feasible to assign likely risk boundaries upon which practical guidance for community consensus can be reached.

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