Brain Cancer and Leukemia and Exposure to Power-Frequency (50- to 60-Hz) Electric and Magnetic Fields

Ruth Douglas Miller, 1 John S. Neuberger, 2 and Kenneth B. Gerald 3

INTRODUCTION

Concern about a possible association between cancer and electric and magnetic fields created by the generation and use of electricity first surfaced in response to the study of childhood cancer in Denver, Colorado, by Wertheimer and Leeper (1). Since then, nearly 90 epidemiologic studies of both occupational and environmental exposure have been published, and numerous reviews (e.g., references 2–6) of this literature exist. Most of the existing reviews have not evaluated the published studies in depth (e.g., references 3 and 7–10). Some (e.g., references 4, 5, and 11) have included several noncancer outcomes, thus broadening their research base and inhibiting extensive review of individual papers. Most have uncritically accepted whatever means of exposure assessment may have been used, when exposure assessment is the most critical and least understood element of these studies of electric and magnetic fields.

This review focuses specifically on published occupational and environmental epidemiologic studies of exposure to power-frequency (50- to 60-Hz) electric and magnetic fields and brain cancer and leukemia. Although several study design issues are discussed, we emphasize techniques for assessing exposure to electric and magnetic fields. The large variation in study design and quality among the papers reviewed precludes any meaningful quantitative analysis (such as meta-analysis), but it is possible among studies of a given design to select those with exposure assessment methodology most likely to rank subjects by actual exposure to electric and magnetic fields and to concentrate on those results. This we have attempted to do. Although the scientific community generally agrees that more research must be done before definitive answers to the question of carcinogenic effects from electric and magnetic fields are known, new research should be guided by the evidence available to date.

BACKGROUND

Appearing in 1979, the first published study indicated that children with cancer seemed to live more commonly near power lines (usually distribution lines but occasionally higher power transmission lines) than did children without cancer (1). Studies of cancer and occupation specifically directed toward electric and magnetic field exposure began to appear in the early 1980s, beginning with leukemia among telecommunications workers (12) and among men in "electrical" occupations (13).

Nearly all studies, and certainly all occupational studies involving measurements, have concentrated on the magnetic rather than the electric field. Although both fields are present around any operating electrical machine or appliance, the electric field is present even when machinery is not operating, does not vary with load current, and does not penetrate the body well. In contrast, the magnetic field is not attenuated by the body at all, is present only when current flows, and varies in proportion to current. Those studies (14, 15) that looked for a relation between measured electric fields and illness found no correlation, further concentrating inquiry on the magnetic field only. Methods of assessing magnetic field exposure have become increasingly more sophisticated with each new study, yet the literature is far from unanimous in concluding that electric and magnetic fields in general or the magnetic field in particular is related to cancer, whether as an initiator or as a promoter. Laboratory evidence of increased cancer rates or other deleterious effects stemming from electric and magnetic fields in animals or cell cultures is weak at best. The strongest evidence to date for any carcinogenic effects from electric and magnetic fields in humans comes from

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epidemiologic studies; therefore, great care must be taken when evaluating them.

METHODS

All epidemiologic studies published through December 1993 that examined electric and/or magnetic field exposure and cancer were collected through a literature search using MEDLINE®. Their references, as well as citations from electric and magnetic field newsletters and any other sources, were cross-checked and additional papers were added to the list. The papers were classified into occupational and environmental studies and, within those two groups, by subject age (adult or child), cancer site (leukemia, brain cancer, or multiple cancers), and study design. Each study’s methods and selected results were summarized in tabular form; odds ratios and confidence intervals were collected in graphs.

Because of the large volume of reports and the great diversity of cancer endpoints examined, we chose to concentrate on those cancers most studied in relation to electric and magnetic fields: brain cancer and leukemia. Almost all occupational studies included cases of white men only, although environmental studies included women and children and, in many cases, all races. Although seven papers were found concerning paternal exposure to electric and magnetic fields and childhood central nervous system cancer, these are not reviewed herein because of the lack of biologic plausibility (electric and magnetic fields are not mutagenic), because electric and magnetic fields cannot be transported from work to the home environment, and because of likely confounding by socioeconomic status.

To ascertain the evidence for an association of the selected cancers with electric and magnetic fields, we listed the odds ratio (or mortality or incidence ratio, as appropriate for each study) and confidence interval (or p value) from all studies for each of the two cancers. If the 95 percent confidence interval included 1.0 as its lower or upper bound or if the p value was equal to 0.05, that odds ratio was noted as of borderline significance.

Almost all occupational studies determined a subject’s exposure from his job title, usually from a death certificate or a cancer registry, but occasionally from an employer’s records or interview. Although studies continue to show significantly higher electric and magnetic field exposure for the “electrical” jobs as a group (16, 17), individual jobs within that category entail highly variable exposures, and some of these are not significantly greater than exposures of “nonelectrical” employees. Therefore, for those studies providing data by individual job title, the odds ratios for each job title were collected and the titles grouped, with the assumption that “higher” exposure can be equated with those jobs where a worker would be close to high 50- to 60-Hz electric currents even for short periods (1–3 hours), or where a worker would be close to moderate currents for long periods. The results of one thorough measurement study (17) were also used to determine those occupations with presumably comparable exposure. Occupational groups used here are shown in table 1. Figures 1 and 2 are the end results of this compilation. Odds ratios (or relative risks or standardized incidence ratios) from all nonproportional mortality ratio occupational studies are shown, ranked by cancer subtype and occupational grouping. Odds ratios are included for all job titles relevant to power-frequency electric and magnetic field exposure as given in the individual papers. A dose-response trend, in grouped data from all studies using occupational titles, showing higher odds ratios and more significant odds ratios for workers in the presumed higher exposure occupations, would be one indication of an association between electric and magnetic fields and that cancer.

The above procedure involved a comparison of data from different studies for each occupational group. A second indication of an electric and magnetic fields-cancer association was sought within each paper, using the assumption that the exposure assessment methods generally use known load data from electricity consumption patterns. The calculation methods generally use known load data from nearby transmission lines and sound computer techniques to calculate magnetic fields due to those lines at the site of a residence at the time of a given load (22, 23). In this evaluation, greater emphasis has been
TABLE 1. Grouping of occupational titles used in the determination of dose-response relations

<table>
<thead>
<tr>
<th>Exposure</th>
<th>Occupational titles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generally greater exposure to electric and magnetic fields (“high”)</td>
<td>Linesmen (power and, where not separated, telephone)</td>
</tr>
<tr>
<td></td>
<td>Power station operators</td>
</tr>
<tr>
<td></td>
<td>Stationary engineers</td>
</tr>
<tr>
<td></td>
<td>Electrical/electronic technicians</td>
</tr>
<tr>
<td></td>
<td>Welders and flame cutters</td>
</tr>
<tr>
<td></td>
<td>Thermoelectric plant workers</td>
</tr>
<tr>
<td>Generally lesser exposure to electric and magnetic fields, greater than background (“moderate”)</td>
<td>Electricians</td>
</tr>
<tr>
<td></td>
<td>Electrical/electronic manufacture/assembly/repair/installation jobs</td>
</tr>
<tr>
<td></td>
<td>Radio/television assembly/repair/installation jobs</td>
</tr>
<tr>
<td></td>
<td>Electrical/electronic engineers (and technicians when not listed separately)</td>
</tr>
<tr>
<td></td>
<td>Telephone linemen</td>
</tr>
<tr>
<td></td>
<td>Utility employees when listed as a single category</td>
</tr>
<tr>
<td></td>
<td>Amateur radio hobbyists</td>
</tr>
<tr>
<td>Exposure to electric and magnetic fields at or near background (“low”)</td>
<td>Radio/telegraph operators</td>
</tr>
<tr>
<td></td>
<td>Telecommunications industry workers</td>
</tr>
<tr>
<td></td>
<td>Radio/television announcers and technicians</td>
</tr>
<tr>
<td>Non-power-frequency exposure</td>
<td>Aluminum reduction plant workers (largely direct current)</td>
</tr>
<tr>
<td></td>
<td>Railway workers (very variable; may be dominated by direct current, 25-Hz or 60-Hz sources) and includes</td>
</tr>
<tr>
<td></td>
<td>Engine and tram drivers</td>
</tr>
<tr>
<td></td>
<td>Track walkers</td>
</tr>
<tr>
<td></td>
<td>Streetcar/subway motormen</td>
</tr>
<tr>
<td></td>
<td>Occupations with microwave/radio-frequency exposure</td>
</tr>
</tbody>
</table>

placed on those studies taking into account changing exposure over time, particularly before and after cancer diagnosis; residence mobility; and multiple field sources (appliance use as well as power line fields). Changing exposure with time may be assessed by asking questions about the extent and duration of appliance use; by obtaining and using power line load data covering an extended period of time; or, in the case of occupational studies, by tracking a worker’s various jobs, titles, and tasks over time and calculating an exposure metric weighted with the duration of work at each task or job title.

RESULTS—OCcupATIONAL STUDIES

Leukemia

Specific details and results of studies using designs other than proportional mortality ratio or proportional incidence ratio, examining leukemia exclusively and using more than registry or census data for exposure classification are summarized in table 2 by year of publication. Registry data are less likely to be complete or accurate than are data from the personal interview or measurements.

Proportional incidence or mortality. Nine studies of this type (13, 17, 24–30) have been conducted since 1982, all among working white males. Only one of these (17) determined exposure by measured magnetic fields; this study found a significant excess of all leukemia at the lowest exposure, but nonsignificant, reduced standardized incidence ratios in higher exposure groups.

Nonconcurrent cohort. Three studies have been published using this design (12, 31, 32). One of these (12) is too small to be conclusive; the other two of approximately equal quality found possibly conflicting results (no repeat job titles).

Case-control. Nine leukemia studies have used this design (17, 25, 33–41) (references 33 and 34 are to the same study, as are references 39 and 40). The best assessments (17, 41) used measurements in determining exposure; both found the less-exposed group, classified by mean magnetic field, to have a higher odds ratio than the more highly exposed groups.

Of all 21 studies, 18 showed a significant or borderline-significant increase in risk in at least one subgroup, and three showed a nonsignificant increase in risk. Although consistently elevated risk ratios are suggestive, the increases in risk are small (many with a risk less than 2.0), and no consistency is apparent in the job title most at risk or in the specific leukemia subtype(s) most commonly elevated. Further, a dose-response trend is not evident when odds ratios from each study are ranked with the job title correlated to presumed exposure, as shown in table 1 (see figure 1). Further discussion follows the review of studies of multiple cancer sites (see below).
FIGURE 1. Odds ratios, relative risks, or standardized incidence ratios (points) and confidence intervals (bars) found in various studies of occupational exposure to electric and magnetic fields and its association with leukemia. Horizontal lines divide exposure categories and cancer types (bottom to top): electrical workers combined, all leukemia; low exposure, all leukemia; moderate exposure, all leukemia; high exposure, all leukemia; high exposure by measurement, all leukemia; electrical workers combined, acute myelogenous leukemia; specific titles in order of increasing exposure, acute myelogenous leukemia; titles in order of increasing exposure, chronic lymphocytic leukemia. "Exposure" refers to exposure assessment method or job title. "Statistics" refers to study design on a four-point scale, where "poor" is univariate statistics, standardized incidence ratio design; "fair" equates to standardized incidence ratio design but with many subjects, or case-control design but very few subjects; "good" is multivariate statistics, case-control design; and "very good" is good with particularly large numbers. "Exp assess" refers to exposure assessment on a four-point scale, where "poor" is job title from incidence records, "fair" is job title from interview, "good" is job title with some measurement, and "very good" is exposure score from measurement. "Comments" refers to significance when the confidence interval is not given and to exposure score from measurement. Abbreviations under "Exposure": E, magnetic field strength; elec, electric or electrical; engr, engineer; tech, technician; contin exp, continuous exposure; indust, industry; pwr sta ops, power station operators; pwr supp, power supply; TV, television; install, installers. Other abbreviations under "Comments": CLL, chronic lymphocytic leukemia; yrs' exp, years' exposure; ns, nonsignificant; leuk, leukemia; CML, chronic myelogenous leukemia; AML, acute myelogenous leukemia; ANLL, acute nonlymphocytic leukemia.
-figure 2. odds ratios, relative risk ratios, or standardized incidence ratios (points, expressed with 1.0 as null) and confidence intervals (bars) found in various studies of occupational exposure to electric and magnetic fields and its association with central nervous system cancers. horizontal lines divide exposure categories (bottom to top): electrical workers combined, low exposure job titles (see table 1), moderate exposure job titles (see table 1), and high exposure job titles (see table 1). for the ratings scale, see the legend to figure 1. sir, standardized incidence ratio. abbreviations under "exp method": exp, exposure; m, magnetic field strength; elec pwr repair, electric power repairmen; ops, operators; util employ, utility employment; util line/serv, utility linesmen/service workers; elec tradesmen, electrical tradesmen; install, installer; elec mfr/repair, electrical manufacturers and/or repairmen; telecomm, telecommunications; tv repair, television repairmen; tele/radio/tv repair, telephone, radio, television repairmen; tech, technician; elec work, electrical workers; em, electric and magnetic; prob exp, probable exposure; definite exp, definite exposure. abbreviations under "comments": m, magnetic field strength; CNS, central nervous system; yrs work, years' work; ns, nonsignificant; astro (astrocyt), astrocytoma.

brain cancer

non-proportional mortality ratio, non-proportional incidence ratio occupational studies with brain cancer as an endpoint, and exposure classified using more than census or death certificate data alone are summarized in table 3.

proportional incidence or mortality. three studies (42-44) have used the proportional incidence or mortality design, all using occupational title for exposure assessment. the best (43) found a significant excess proportion of glioma and astrocytoma among electrical workers.

nonconcurrent cohort. one nonconcurrent cohort study (45) found no significant increase in risk for electricians, power line workers, or telecommunication workers but a significant increase in risk for welders and metal cutters.

Case-control. Six studies of brain tumors have used the case-control design (43, 46-50). The best of them in terms of exposure assessment and study size (46) found elevated risks of astrocytoma among electricians, power and telephone linesmen, and electronics manufacture or repair workers. Two other studies using good exposure assessment methods (48, 49).
## TABLE 2. Epidemiologic studies of leukemia and occupational exposure to 50- to 60-Hz electric and magnetic fields

<table>
<thead>
<tr>
<th>Study and date (reference no.)</th>
<th>Study type</th>
<th>Location</th>
<th>No. of subjects</th>
<th>EMF assessment method</th>
<th>Other risk factors</th>
<th>Selected results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flodin et al., 1986 (36)</td>
<td>Case-control</td>
<td>Linkoping, Norrkoping, Orebro, Umea, and Jonkoping, Sweden, incidence from 1977 to 1982</td>
<td>59 acute myeloid leukemias, 354 controls</td>
<td>Occupational title from personal questionnaire</td>
<td>Medical care, drugs, diagnostic radiography, gamma radiation, solvent exposure, smoking habits</td>
<td>LRR* = 3.8 (95% CI* 1.5–9.5) for electrical workers (technicians, welders, and computer/telephone technicians)</td>
</tr>
<tr>
<td>Stern et al., 1986 (37)</td>
<td>Case-control</td>
<td>Portsmouth, NH, employed between 1952 and 1977, deceased by 1981</td>
<td>53 leukemia deaths, 212 controls (white males only)</td>
<td>Occupational title from employer’s records; complete work history with both workplace and job title</td>
<td>Solvent exposure, ionizing radiation, occupational history</td>
<td>Significant associations for both lymphatic and myeloid leukemia with work as electrician and welder</td>
</tr>
<tr>
<td>Preston-Martin and Peters, 1988 (38)</td>
<td>Case-control</td>
<td>Los Angeles, CA, incidence from 1979 to 1985</td>
<td>130 cases, 130 controls (males only)</td>
<td>Occupational title and other exposures from telephone interview</td>
<td>Down’s syndrome in relative, ORw* = 25.4 (95% CI 2.78–232.54) for welders</td>
<td></td>
</tr>
<tr>
<td>Bowman et al., 1992 (17)</td>
<td>Case-control portion</td>
<td>Los Angeles County, CA, incidence from 1972 to 1989</td>
<td>2,192 leukemias (112 exposed cases, 62,671 cancer controls (males only)</td>
<td>Occupational title from cancer registry combined with extensive magnetic field measurements</td>
<td>None</td>
<td>Borderline-significant associations with magnetic field exposure, but no trend with increasing exposure</td>
</tr>
<tr>
<td>Richardson et al., 1992 (40)</td>
<td>Case-control</td>
<td>Paris, France, incidence from 1984 to 1988</td>
<td>185 leukemia cases, 513 hospital controls</td>
<td>Occupational history (job titles and tasks) from patient interview, combined with job-exposure matrix</td>
<td>Benzene and other solvents, exhaust gas, pesticides, herbicides, ionizing radiation, chemotherapy, radiotherapy</td>
<td>Exposure to EMF* significant only if electric arc welders are excluded; significant associations with herbicides, benzene</td>
</tr>
<tr>
<td>Matanoski et al., 1993 (41)</td>
<td>Nested case-control within cohort</td>
<td>United States (workers for AT&amp;T, 1975–1980)</td>
<td>124 leukemia cases with three controls/case (white males only)</td>
<td>Occupational title and/or occupational history from personnel records; weighted exposure score based on measured field and job duration</td>
<td>None</td>
<td>No significant associations with EMF</td>
</tr>
</tbody>
</table>

* LRR, logistic rate ratio; CI, confidence interval; ORadj, adjusted odds ratio; EMF, electric and magnetic fields.
<table>
<thead>
<tr>
<th>Study and data (reference no.)</th>
<th>Study type</th>
<th>Location</th>
<th>No. of subjects</th>
<th>EMF* assessment method</th>
<th>Other risk factors</th>
<th>Selected results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lin et al., 1985 (43)</td>
<td>Case-control portion</td>
<td>Maryland, deaths from 1969 to 1982</td>
<td>951 brain tumors, 951 control deaths (non-malignant cause of death) (white males only)</td>
<td>Occupational title from death certificate and ranking of occupations for exposure to EMF</td>
<td>None</td>
<td>OR* = 2.15 (95% CI* 1.10–4.06) for occupations with definite electric and magnetic exposure and glioma/astrocytoma</td>
</tr>
<tr>
<td>Thomas et al., 1987 (46)</td>
<td>Case-control</td>
<td>Northern New Jersey and Philadelphia, PA (deaths from 1979 to 1981); gulf coast of Louisiana (deaths from 1978 to 1980)</td>
<td>435 brain tumors, 386 controls (excluding brain tumors, epilepsy, stroke, suicide, or homicide) (white males only)</td>
<td>Job History from interview of next-of-kin and ranking of occupations for microwave/radio-frequency exposure</td>
<td>Soldering, microwave/radio-frequency exposure</td>
<td>Significant elevated risk of astrocytoma for lower exposure group (electronics/manufacturing/repair) and not for higher exposure group (electricians, linemen)</td>
</tr>
<tr>
<td>Speers et al., 1988 (47)</td>
<td>Case-control</td>
<td>East Texas, deaths from 1969 to 1978</td>
<td>202 gliomas, 238 controls (excluding brain tumors) (males only)</td>
<td>Industrial and occupational titles from death certificate; ranking of occupations for exposure to EMF from Lin et al. (43)</td>
<td>Ranking of occupations for exposure to chemicals and ionizing radiation</td>
<td>Significantly elevated odds ratios for utility workers, electricians; significant trend with increased likelihood of exposure</td>
</tr>
<tr>
<td>Schlehofer et al., 1990 (48)</td>
<td>Case-control</td>
<td>Rhein-Neckar-Odenwald area of Germany, incidence from 1987 to 1988</td>
<td>226 cases, 418 residential controls (males and females)</td>
<td>Complete job history and chemical exposures from interview; jobs grouped similarity to Lin et al. (43)</td>
<td>Age, sex, tobacco use</td>
<td>Elevated risk for women, but not men, in &quot;high-exposure&quot; jobs</td>
</tr>
<tr>
<td>Mack et al., 1991 (49)</td>
<td>Case-control</td>
<td>Los Angeles County, CA, deaths from 1980 to 1984</td>
<td>272 brain tumors, 272 controls (males only)</td>
<td>Job history from personal questionnaire; including duration of occupation</td>
<td>Listing of chemicals and welding utilized on the job</td>
<td>OR = 10.3 (95% CI 1.3–80.8) for astrocytomas in individuals employed more than 10 years; majority of these patients had been electricians (n = 8) or electrical engineers (n = 3)</td>
</tr>
<tr>
<td>Ryan et al., 1992 (50)</td>
<td>Case-control</td>
<td>Adelaide, Australia, incidence from February 1987 to March 1990</td>
<td>110 glioma cases, 60 meningioma cases, 417 controls (men and women)</td>
<td>Job History from personal interview; use of electric blanket, waterbed</td>
<td>Use of tobacco, alcohol, medications, cosmetics; diet, water source, ionizing radiation on job and from diagnostic radiography</td>
<td>No increased risk for meningioma; increased risk for glioma in women exposed to cathode-ray tubes</td>
</tr>
</tbody>
</table>

* EMF, electric and magnetic fields; OR, odds ratio; CI, confidence interval.
found increased risks of brain cancer associated with long-term employment in electrical occupations.

Overall, of 10 studies of brain cancer and occupational exposure to magnetic fields, all find at least one significant elevated risk. While “electrician” and “electrical engineer” recur as job titles at risk in four studies, two others find no elevation in risk for these jobs. Those few studies that have looked at central nervous system cancer subtypes find glioma or astrocytoma to be consistently associated and meningioma not to be associated. Further discussion follows a review of studies of multiple cancers.

Multiple cancer sites

The bulk of occupational epidemiologic studies of cancer have examined multiple disease endpoints. Results of selected reviewed studies are summarized in table 4; only those studies giving results for brain cancer and/or leukemia are listed. Studies included in table 4 assessed exposure with some measurements or examined an occupational cohort that should include significantly exposed workers. We have concentrated on studies using at least some workplace EMF measurements to determine exposure.

Proportional incidence or mortality. An early proportional mortality survey in Washington (51) found significantly elevated mortality from brain cancer, all leukemias combined, and acute leukemia. This study examines a large population and uses the appropriately narrowed confidence interval to adjust for a large number of statistical tests.

Nonconcurrent cohort. A total of 16 papers cover studies of the nonconcurrent cohort design; most report results for both central nervous system cancer and leukemia (52–67). Overall, more odds ratios are elevated than are reduced, but all ratios are weak and there is no real consistency in particular job titles (and therefore presumed exposures) indicated. All these cohort studies, except for one (67), use job title as a surrogate for electric and magnetic field exposure. Clearly the best in terms of exposure assessment, using measured fields and time-average weighting to account for changing tasks over time, this study (67) found no significant associations between cancer and magnetic field exposure.

Case-control. Five studies of this design were reviewed (67–71). Of those with the best exposure assessment as defined above (67, 71), the smaller study found no associations (67), while the larger found significant associations between different electric and magnetic field exposure metrics and chronic lymphocytic leukemia and brain cancer.

Summary of results of occupational studies

An examination of the tabulated results of the studies reveals evidence for an association of leukemia and central nervous system tumors with employment in an “electrical” occupation. However, when results are examined at the level of individual job titles, the data become much more scattered, sparse, and hard to summarize. For this reason, to determine if patterns exist, we made an effort to gather the conclusions of each study by job title.

We reviewed a total of 124 calculations of odds ratios for leukemia (see figure 1 for nonproportional mortality ratio studies). Forty-one, or 33 percent, were significantly elevated. Four studies showed internal dose-response trends with either duration or intensity of exposure (41, 62, 65, 71) although, when occupations are ranked by presumed exposure, no trend with increasing exposure is apparent across studies. Neither are the results from recent studies with excellent exposure assessment (67, 71) any different from those of older or methodologically weaker studies. No single subtype of leukemia dominates these results; some earlier survey-style studies found associations with acute or chronic myeloid leukemia, while more recent Swedish study (71), in which exposure was assigned by actual measurements, found an association only with chronic lymphocytic leukemia. Despite these inconsistencies, most odds ratios in figure 1 are greater than one, suggesting that some aspect of these occupations, whether electric and magnetic fields or something else, may have some promoting effect on adult leukemia. We conclude that there is reasonable evidence for a weak association (odds ratio between 1.0 and 2.0) between adult leukemia and occupational exposure to electric and magnetic fields but that electric and magnetic fields cannot account for the majority of leukemia cases among working men.

A total of 73 calculations of odds ratios for adult cancer of the central nervous system were examined; figure 2 shows results from nonproportional mortality ratio studies. No trend is apparent in figure 2, although the combined occupation category seems to have a consistently elevated risk. Although most odds ratios are greater than one, very few are statistically significant. The studies with the best exposure assessment (67, 71) show odds ratios that are not higher than those found in other studies. Figure 2 would indicate some evidence for a weak association between electric and magnetic fields and adult brain cancer (odds ratio less than 2.0), because more odds ratios are elevated than are reduced. However, any association appears to be weaker than evidence for leukemia, and the results of the highest quality studies would indicate, at the least,
<table>
<thead>
<tr>
<th>Study and data (reference no.)</th>
<th>Study type</th>
<th>Location</th>
<th>No. of subjects</th>
<th>Assessment method of EMF*</th>
<th>Other risk factors</th>
<th>Selected results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vagero et al., 1985 (55)</td>
<td>Nonconcurrent cohort (SMR (mortality))</td>
<td>Sweden, employed ≥6 months between 1956 and 1960; incidence from 1958 to 1979</td>
<td>2,051 men followed, 867 women followed</td>
<td>Work history in a telecommunications company</td>
<td>Oil mist; trichloroethylene; grinding, polishing, and degreasing (by department)</td>
<td>SMR* = 1.0 (95% CI: 0.3–2.3) for nervous system cancer in males; no data for relevant cancers in females</td>
</tr>
<tr>
<td>Spinelli et al., 1991 (63)</td>
<td>Nonconcurrent cohort (SIR* and SMR)</td>
<td>British Columbia, Canada, incidence/mortality from 1954 to 1985</td>
<td>4,213 men followed (males only)</td>
<td>Work history in aluminum reduction plant and associated power-generating station</td>
<td>Coal-tar pitch volatiles</td>
<td>Elevated incidence and mortality for brain and central nervous system cancer but not for leukemia; no significant associations found with EMF</td>
</tr>
<tr>
<td>Flanderus et al., 1993 (71)</td>
<td>Case-control</td>
<td>Sweden, incidence from 1983 to 1987</td>
<td>250 leukemia cases, 261 brain tumor cases, 1,121 controls (males only)</td>
<td>Work history from questionnaire combined with 6-hour workplace measurements; tasks categorized by mean, median, standard deviation, and time &gt;2 mG from measurement data</td>
<td>Exposure to benzene, ionizing radiation, solvents, smoking; urban/rural residence</td>
<td>Significantly elevated risks of chronic lymphocytic leukemia and brain cancer with high measured magnetic field exposure; apparent trend of increasing risk of chronic lymphocytic leukemia with increasing exposure</td>
</tr>
<tr>
<td>Sahi et al., 1993 (67)</td>
<td>Nonconcurrent cohort (mortality)</td>
<td>California, employed between 1960 and 1988; deaths through 1989</td>
<td>36,221 employees of an electric utility followed (males only)</td>
<td>Exposed workers: usual occupation near energized equipment; referent: any other occupation</td>
<td>None</td>
<td>No increased rate of leukemia or brain cancer among electrical workers; no apparent dose-response trend with years worked</td>
</tr>
<tr>
<td>Sahi et al., 1993 (67)</td>
<td>Case-control</td>
<td>California (same as above)</td>
<td>44 leukemia cases, 32 brain cancer cases, 1,424 controls (may include cancer cases diagnosed later than matched case) (males only)</td>
<td>Score based on mean, median, 99th percentile, or time fraction over 10- or 50-mG magnetic field measurements in occupations, weighted by years of work in each occupation</td>
<td>None</td>
<td>No association between exposure to EMF and leukemia or brain cancer; no significant odds ratio for any individual job title</td>
</tr>
</tbody>
</table>

* EMF, electric and magnetic fields; SMR, standardized mortality ratio; CI, confidence interval; SIR, standardized incidence ratio.
that factors other than electric and magnetic fields are involved.

RESULTS—ENVIRONMENTAL STUDIES

Adult leukemia

Of the three case-control studies of this cancer found in table 5 (18, 72, 73), two found elevated odds ratios (72, 73), but none was statistically significant. The third study (18) focused on electric blanket use as a measure of exposure and found no significant association.

Adult brain cancer

Only one environmental case-control study has been conducted on adult brain cancer (table 5). That recent study in Adelaide, Australia (50), found an increased risk of glioma for women, but not men, who reported working with cathode-ray tubes. No significant increases or decreases in risk were found for use of an electric blanket or heated waterbed or occupational exposure to high electric currents.

Adult multiple cancer sites

Nonconcurrent cohort. Two studies of this type have been published (74, 75) (table 6). Both used distance from electric installations as the EMF exposure metric; neither found any statistically significant results.

Case-control. Three papers (58, 76, 77) describe two studies of this type (table 6). One found a statistically significant increase in the risk of nervous system tumors associated with high wire code residences (58). The other found a borderline significant association between leukemia or lymphoma and residence near high power lines. No significant correlation was seen between high calculated fields and cancer incidence (77); this is the best exposure assessment method used.

Childhood leukemia

Two case-control studies examined childhood leukemia alone (15, 78); one is included in table 7. These workers found a significant association between leukemia and wire code and an elevated nonsignificant association for measured field above 2.68 mG, as well as significant associations with some appliances and household contaminants. The second study is significantly flawed in design (78); the formula used to rank homes by levels of electric and magnetic fields assumes that more wires equate to higher fields, and this is demonstrably false (79).

Childhood multiple cancer sites

Childhood cancer in general was the focus of seven reviewed case-control studies (1, 14, 21, 23, 80–82); the two earliest are not shown in table 7. The best (23, 81, 82) found somewhat conflicting results: an elevated risk of leukemia in one (23), of central nervous system tumors in another (82), and of neither in the third. Small study size is a factor in two of these (81, 82), but all three used the same, well-designed exposure assessment protocol calculating historical magnetic fields with a computer model using historical power load data.

Summary of results of environmental studies

Adult leukemia has been examined in five environmental studies, four of which are of high quality statistically (see figure 3). None has found significant results. We conclude that the evidence of an association between adult leukemia and environmental exposure to electric and magnetic fields is extremely weak. This finding, in combination with that for occupational studies, reinforces the suggestion that further occupational work should be done in this area before attempting an environmental study.

Childhood leukemia has been examined in eight studies, three of which had statistically significant results (see figure 4). No trend is apparent with improved exposure assessment, though within a study the wiring code produces more significant results than do spot measurements (14). All studies suffer from small numbers in the higher exposure category. As almost all odds ratios are greater than 1.0, and a recent well-conducted study found significant results (23), we conclude that there is weak evidence for an association of childhood leukemia with electric and magnetic fields and, further, that large studies are warranted.

Seven studies have evaluated the association between childhood cancers of the central nervous system and electric and magnetic fields (see figure 4). Three found statistically significant elevated results, though one of those was of poor quality. The recent, nonsignificant studies are well designed but too small to be definitive. If any trend exists in the data, it is that improved exposure assessment weakens any association.

DISCUSSION

To summarize numeric results, the occupational studies with the best exposure assessment methods found a nonsignificant elevated risk of brain cancer and a significant elevated risk of chronic lymphocytic leukemia (but not of all leukemia) related to occupational exposure to electric and magnetic fields. The best of the environmental studies in terms of exposure...
<table>
<thead>
<tr>
<th>Study and date (reference no.)</th>
<th>Study type</th>
<th>Location</th>
<th>No. of subjects</th>
<th>Assessment method of EMF*</th>
<th>Other risk factors</th>
<th>Selected results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preston-Martin et al., 1988 (18)</td>
<td>Case-control</td>
<td>Los Angeles County, CA, incidence from July 1979 to June 1985</td>
<td>224 leukemia cases, 228 neighborhood controls</td>
<td>Electric blanket use (yes/no: ever used regularly)</td>
<td>Diagnostic radiographs, welding occupation, farm residence, socioeconomic status, chemical exposures</td>
<td>OR* = 0.9 (95% CI* 0.5–1.6) for acute myelogenic leukemia; OR = 0.8 (95% CI 0.4–1.6) for chronic myelogenic leukemia</td>
</tr>
<tr>
<td>Severson et al., 1988 (72)</td>
<td>Case-control</td>
<td>Western Washington State, incidence from 1981 to 1984</td>
<td>114 acute nonlymphocytic leukemia cases, 133 living controls</td>
<td>External electrical wiring configurations (W and L* code), residential magnetic field measurements (spot measurement in homes, 24-hour measurement in a few homes)</td>
<td>Occupational history, ionizing radiation, medical history, smoking history, pet ownership, education</td>
<td>OR = 1.25 (95% CI 0.35–4.48) for highest weighted mean exposure in high power configuration; no significant risk by spot measurements</td>
</tr>
<tr>
<td>Coleman et al., 1989 (73)</td>
<td>Case-control</td>
<td>Southeast England (suburban London), registered from 1965 to 1980</td>
<td>771 leukemia cases, 1,432 cancer controls (excluding lymphoma), 231 population controls</td>
<td>External electrical equipment type and power loading (overhead lines and substations within 100 m)</td>
<td>None</td>
<td>No significant associations between leukemia and residence near high voltage equipment; no significant trends with distance or weighting for maximum loads</td>
</tr>
<tr>
<td>Ryan et al., 1992 (50)</td>
<td>Case-control</td>
<td>Adelaide, Australia, incidence from February 1987 to March 1990</td>
<td>110 glioma cases, 60 meningioma cases, 417 controls (men and women)</td>
<td>Electric blanket/waterbed use and job history from personal interview</td>
<td>Use of tobacco, alcohol, medications, cosmetics; diet; water source; ionizing radiation on job and from diagnostic radiographic examinations</td>
<td>RR* = 1.48 (95% CI 0.83–2.63) for glioma and use of an electric blanket</td>
</tr>
</tbody>
</table>

* EMF, electric and magnetic fields; OR, odds ratio; CI, confidence interval; W and L, Werhelmer and Leeper; RR, relative risk.
<table>
<thead>
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<th>No. of subjects</th>
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<th>Other risk factors</th>
<th>Selected results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wertheimer and Leeper, 1982 (76)</td>
<td>Case-control</td>
<td>Denver and suburbs, Longmont, and Boulder, CO, deaths from 1967 to 1975</td>
<td>1,179 addresses of adult cancer cases (275 alive, 904 dead), 1,179 addresses of controls</td>
<td>External wiring codes for house occupied longest of 3–10 years before diagnosis</td>
<td>Socioeconomic level</td>
<td>OR* = 139 (p &lt; 0.0001) for total cancer, all four locations combined; OR = 164 (p &lt; 0.005), Longmont; OR = 143 (p &lt; 0.01), Boulder</td>
</tr>
<tr>
<td>McDowall, 1986 (74)</td>
<td>Nonconcurrent cohort (SMR)</td>
<td>East Anglia, United Kingdom, deaths from 1971 to 1983</td>
<td>7,831 individuals followed</td>
<td>Distance from electrical installations (&lt;50 m from substation, &lt;30 m from transmission line)</td>
<td>Occupation</td>
<td>SMR* = 154 (95% CI* 42–394) for women and leukemias</td>
</tr>
<tr>
<td>Wertheimer and Leeper, 1987 (58)</td>
<td>Case-control</td>
<td>Colorado, deaths from 1967 to 1975</td>
<td>1,179 addresses of cancer cases; 1,179 addresses of controls; 3,375+ cancers in followed-up group</td>
<td>External wiring codes</td>
<td>None</td>
<td>OR = 227 (p ≤ 0.05) for nervous system tumors</td>
</tr>
<tr>
<td>Youngson et al., 1991 (77)</td>
<td>Case-control</td>
<td>Northwest and Yorkshire, England, registered from 1983 to 1985</td>
<td>3,144 cases of leukemia and lymphoma, 3,144 noncancer controls</td>
<td>Calculated maximum magnetic field from measured distance to line and known maximum load (V ≥ 33 kV) or estimated maximum load (V &lt; 11 kV) over past 5 years</td>
<td>None</td>
<td>OR = 1.29 (95% CI 0.99–1.68) for distances less than 50 m; OR = 1.87 (95% CI 0.79–4.42) for ≥3.0 mG magnetic field (both for all cases combined); OR = 1.22 (95% CI 0.75–1.98) for distances less than 50 m and myeloid leukemia</td>
</tr>
<tr>
<td>Schreiber et al., 1993 (75)</td>
<td>Nonconcurrent cohort (SMR)</td>
<td>Resident in Limmel district of Maastricht, Netherlands, between 1956 and 1981 inclusive</td>
<td>3,549 individuals followed; 431 deaths</td>
<td>&quot;Exposed&quot; lived at least 5 years within 100 m of substation or one of two 161-kV lines in district</td>
<td>None</td>
<td>No significant associations between proximity to high-voltage equipment and leukemia or brain cancer</td>
</tr>
</tbody>
</table>

* EMF, electric and magnetic fields; OR, odds ratio; SMR, standardized mortality ratio; CI, confidence interval.
### TABLE 7. Epidemiologic studies of childhood cancers and environmental exposure to 50- to 60-Hz electric and magnetic fields

<table>
<thead>
<tr>
<th>Study and date (reference no.)</th>
<th>Study type</th>
<th>Location</th>
<th>No. of subjects</th>
<th>Assessment method of EMF*</th>
<th>Other risk factors</th>
<th>Selected results</th>
</tr>
</thead>
<tbody>
<tr>
<td>London et al., 1991 (15)</td>
<td>Case-control</td>
<td>Los Angeles County, CA, incidence from 1980 to 1987</td>
<td>232 childhood leukemia cases, 232 controls (aged ≤10 years)</td>
<td>24-hour magnetic field measurements in child's bedroom, spot measurements of magnetic and electric fields, and wiring configuration, or house lived in longest between conception and diagnosis</td>
<td>Medical history, medications use, parental occupations, appliance use, environmental chemicals</td>
<td>Elevated odds ratio but not significant for measured magnetic field; elevated, significant odds ratio for wire code, some electric appliances, mother's occupational exposure to EMF</td>
</tr>
<tr>
<td>Savitz et al., 1988 (14)</td>
<td>Case-control</td>
<td>Denver, CO, incidence from 1976 to 1983</td>
<td>320 cancer cases (319 wired-coded homes, 128 measured homes), 259 controls (207 measured homes) (aged 0–14 years)</td>
<td>External electrical wiring configuration plus spot electric and magnetic field measurements under low and high power use conditions in several rooms</td>
<td>Family history of cancer, exposure to diagnostic radiography, medications in utero, parental occupations and education, mother's and child's illness history, race</td>
<td>OR* = 2.04 (95% CI* 1.11–3.76) for brain cancer cases and two-level wiring codes; OR = 1.54 (95% CI 0.90–2.63) for all leukemia cases and two-level wiring codes</td>
</tr>
<tr>
<td>Savitz et al., 1990 (21)</td>
<td>Case-control</td>
<td>Metropolitan Denver, CO, incidence from 1976 to 1983</td>
<td>252 cancer cases, 222 controls (aged 0–14 years)</td>
<td>Electric appliance use from questionnaire; wiring configuration code; spot measurement of electric and magnetic fields in the home if same as home prior to diagnosis</td>
<td>Family history, cigarette smoking, alcohol use, occupational history, diet, medications, radiographic examinations, family income, wire code at diagnosis</td>
<td>Significant elevated risk of brain cancer and leukemia with prenatal maternal electric blanket use, particularly in first trimester</td>
</tr>
<tr>
<td>Feychting and Ahlbom, 1993 (23)</td>
<td>Case-control</td>
<td>Sweden, incidence from 1960 to 1985</td>
<td>39 leukemia, 33 central nervous system cancer, 19 lymphoma, and 51 other cancer cases, 558 controls, all resident within 325 m of 200- or 400-kV lines in Sweden (aged 0–15 years)</td>
<td>Proximity to power lines; spot measurements of magnetic field in home; calculated field due to all nearby overhead lines using power load at time of diagnosis</td>
<td>Rural or urban residence, duration of residence, single family home or apartment, socioeconomic status, nitrogen dioxide exposure (traffic density)</td>
<td>Significant increased risk of leukemia with high calculated magnetic field and proximity to power lines; no increased risk of brain tumors</td>
</tr>
<tr>
<td>Olsen et al., 1993 (81)</td>
<td>Case-control</td>
<td>Denmark, incidence from 1968 to 1986</td>
<td>833 leukemias and 624 central nervous system cancers, 4,786 controls chosen from entire population of Denmark (aged 0–15 years)</td>
<td>Proximity to power lines and substations; calculated field due to all nearby lines using average yearly power load; total μT-years exposed</td>
<td>Socioeconomic status, urban, suburban, or rural neighborhood</td>
<td>OR = 6.0 (95% CI 0.8–44) for leukemia and calculated field ≥0.4 μT; OR = 6.0 (95% CI 0.7–44) for central nervous system tumors and calculated field ≥0.4 μT</td>
</tr>
<tr>
<td>Verkasalo et al., 1993 (82)</td>
<td>Cohort</td>
<td>Finland, incidence from 1970 to 1989</td>
<td>134,800 children resident within 500 m of 110- to 400-kV power lines and in calculated fields ≥0.01 μT (aged 0–19 years)</td>
<td>Calculated field due to all nearby lines ≥110 kV using average yearly power load; total μT-years exposed</td>
<td>None</td>
<td>SIR* = 4.2 (95% CI 1.4–9.9) for central nervous system tumors in boys and calculated field ≥0.2 μT, no increased risk in girls; SIR = 1.6 (95% CI 0.32–4.5) for leukemias and calculated field ≥0.2 μT (both sexes)</td>
</tr>
</tbody>
</table>

* EMF, electric and magnetic fields; OR, odds ratio; CI, confidence interval; SIR, standardized incidence ratio.
FIGURE 3. Odds ratios (points) and confidence intervals (bars) found in various studies of environmental exposure (exp) to electric and magnetic fields and its association with adult leukemia. For ratings scale, see the legend for figure 1. Note: "distance to line" is rated as fair only for the short distance of 50 m; 100 m would include many unexposed subjects. Abbreviations under "exposure method": calc B, calculated magnetic field strength; TWA meas B, time-weighted average measured magnetic field strength; elec blanket, electric blanket. Abbreviations under "comments": B, magnetic field strength; BLL, blood lead level; all leuk, all leukemia; ANLL, acute myeloid leukemia; CLL, chronic lymphocytic leukemia; all leuk, all leukemia; ALL, acute lymphocytic leukemia; CML, chronic myelogenous leukemia; AML, acute myelogenous leukemia.

FIGURE 4. Odds ratios (points) and confidence intervals (bars) found in various studies of environmental exposure (exp) to electric and magnetic fields and its association with childhood cancers. Horizontal line separates odds ratios for leukemia (below) and central nervous system cancers (CNS) (above). For ratings scale, see the legend for figure 1. The electric blanket use rating varies according to the specificity of the "duration of use" data collected. Abbreviations under "exposure method": calc pwrline B, calculated powerline magnetic field strength; spot B meas, spot magnetic field strength (measured); maternal elec, mother's electric blanket; elec blanket, electric blanket; dist to line/sub, distance to line or substation. Exp assess, exposure assessment. Abbreviations under "comments": pwr, power; spot B, spot magnetic field strength;  all leuk, all leukemia; ALL, acute lymphocytic leukemia; VH, very high; VL, very low; CML, chronic myelogenous leukemia; AML, acute myelogenous leukemia.

assessment found a borderline-significant elevated risk of childhood leukemia and nonsignificant elevated risks of adult leukemia and childhood brain cancer, though the studies of adult cancer are weaker in exposure assessment design.

Exposure assessment methods are discussed in some detail below; however, it is appropriate to mention a few other considerations. Other important factors that must be evaluated in weighing the actual risk of cancer include strength of the association, attributable risk.
consistency within and between studies and with national cancer trends, and dose-response relations (83). Moreover, the consistent slight elevation in risk across studies (see figures 1 and 2) raises the question of publication bias.

The strength of the association for these cancers tends to be in the weak-to-moderate zone, generally under 2.0. Attributable risk calculations are unfortunately lacking for almost all of these published studies. Although "electrical" occupations in general appear to be associated consistently with leukemia and brain cancer, differences appear when results are examined for specific occupations. The particular subtypes of leukemia and of brain cancer associated with magnetic fields are not consistent between studies. Central nervous system tumors are increasing in incidence, while total adult leukemia is decreasing in incidence in the United States. A final inconsistency: Studies differ in their determination of risk for men or women for both leukemia and brain cancer.

The dose-response relation has been demonstrated in a few studies, particularly those of brain cancer, which used surrogate measures of exposure (41, 44, 62, 80). However, for many studies no such trend is apparent, whether within or, in the occupational case, between studies, when looking at different occupations with different levels of exposure. For leukemia, most frequently recurring job titles are not those of highest exposure (telephone or telegraph operators, radio or television repairmen), while more highly exposed occupations occur less often (power linesmen, welders). On the other hand, for brain cancer the titles that appear repeatedly are more associated with high magnetic fields (welders, electricians, utility workers).

That many published studies used different methods and different populations yet consistently arrived at slightly elevated risk ratios raises the possibility of publication bias; that is, studies that do not find risk may not be submitted for publication or may not be accepted. However, it is the nature of the electric and magnetic fields issue in particular that negative results would be viewed as desirable by many and would be published if submitted. In addition, figures 1 and 2 contain many data points from studies that looked at a broad range of cancers; such papers would be published because of positive associations found with other cancers, regardless of their findings for brain cancer or leukemia, even if publication bias were a problem.

Exposure assessment of electric and magnetic fields remains the most serious deficiency in these published studies. Occupational title has been utilized almost exclusively as an indirect measure of work exposure. Where measurements of electric and magnetic fields have been used, as opposed to job title, the risks from electric and magnetic fields have sometimes weakened or vanished.

Most occupational studies examined a category of "electrical worker" that lumped all presumed exposed occupations together, almost certainly combining occupations with exposures near background levels with those with significantly high exposure. This error should result in odds ratios shifted toward unity, unless the observed association is not with electric and magnetic fields at all but with some other factor constant over the various jobs. Yet as has been discussed, a trend of increasing odds ratios with increasing refinement of exposure grouping is not visible in figures 1 and 2. Not all jobs examined entailed exposure to power-frequency fields and, because so little is known of possible mechanisms for interaction of such fields with biologic tissues, it is unwise to combine 50- to 60-Hz exposures with direct current, 12–25 Hz, or radio-frequency exposures.

The most recent occupational studies that have relied upon measurements for exposure assessment (67, 71) are much stronger than the previous survey-type publications. Recently, results were published from a long-awaited case-control study of men employed in electric power utilities in Ontario and Quebec, Canada, and in France (84). This study used week-long measurements on many workers to estimate exposures on a task-by-task basis. Expert judgment and some modeling of variation in power load were used to develop scaling factors to adjust for historical exposure patterns. Despite much more accurate estimations of exposure to electric and magnetic fields, these three studies do not find stronger estimates of increased risk. The French-Canadian study in particular used a near-ideal exposure assessment methodology, which coupled with the large population included suggests at least that electric and magnetic fields are not likely a significant cause of cancer for most people.

In the environmental studies, three different exposure assessment methods have primarily been utilized: wire codes, use of electric appliances, and measured or calculated field levels. The very recently published study of childhood brain cancer in Los Angeles (85) used all of these methods except calculated fields. The wire coding method (1) has the significant advantage of ease of use; that is, an investigator need not gain access to the subject's home for measurements. Moreover, because the wires outside a home presumably do not change over long periods of time, this measure may more accurately assess exposure for many years prior to the onset of the cancer of interest, whereas measurements determine current and field levels only at one moment in time. On the other hand, some wire
coding papers (reference 78 and possibly reference 1) use the assumption that multiple wires lead to higher magnetic field intensities. This is demonstrably false; as a general rule, the magnetic field near a three-phase line will be less than that near a single line carrying the same current per phase. A similar exposure assessment method to that of wire codes, simple distance to visible electrical structures, including transmission and distribution lines and substations, has been used in several studies (22, 73, 74). Although equally as convenient as the "wire codes" method, the distance to an electrical structure—when not correlated with any measure of the load carried by that structure—can easily result in gross misclassification of actual exposure to electric and magnetic fields (86). In addition, buried lines do produce magnetic fields, which are not shielded by the ground and may in some instances actually lead to higher exposures of subjects not near above-ground electrical structures (87).

When appliance use is assessed as a measure of exposure, it is important to obtain not just a report of "ever used" but some measure of duration of use over time and intensity of use per hour or per day. From such data the presence of a dose-response relation can be ascertained. While some studies did collect such information, others did not; the Los Angeles study (85) does not record any finer division of duration of exposure than exposure during pregnancy or child's lifetime. Recall bias is always a potential problem in retrospective studies evaluating appliance use, particularly if proxy respondents are interviewed.

Field measurements varied in their extent in each environmental study, from single-time ("spot") measurement at the front door of a residence through spot measurements in one to several rooms of a home to a 24-hour record of magnetic field levels at one or two sites in a home. More elaborate measurement techniques are being used currently; the Los Angeles study (85) used all of the above plus spatial mapping of magnetic field profiles around homes and measurement of static magnetic fields outside homes. Field calculations generally are performed with a computer, which basically finds the magnetic field from all given transmission line sources using the Biot-Savart law and data on conductor placement and load. Because the needed load data from several years prior to the beginning of a project are rarely maintained in the United States, this calculation technique has to date been used only in studies in Europe (23, 81, 82). It should be very accurate for determining exposure to electric and magnetic fields from transmission lines and is certainly preferable to wire codes, but it ignores any exposure received from local, in-house sources such as house wiring, appliances, and ground currents. Such in-home fields are generally greater in magnitude, temporal variability, and bandwidth (frequency range) than are fields generated by power lines, and any one of these factors may be more important from a biologic viewpoint than the relatively uniform (in time and space) fields from a transmission line. The best way of assessing environmental exposure is to have subjects carry magnetic field meters with them throughout an entire day or week, while noting activities and movements. This is obviously time consuming, expensive, and in some cases unreasonable, as when a seriously ill patient is a case.

It has been claimed, and perhaps rightly, that present-day short-term (5 minutes to 24 hours) measurements of magnetic fields may not be adequate indicators of true long-term exposure, while a person living for a long time relatively closer to high-current power lines will have a greater exposure to electric and magnetic fields than one living farther away, regardless of the absolute field strengths at the two locations (88). Such classification methods, however, assume that the power lines are the major source of exposure to electric and magnetic fields while, for the majority of the population, in-home sources are far more important. The results of the recent Los Angeles study (85) are interesting in this respect. In general, for all measured fields, a higher wire code is indicative of a higher magnetic field, but the measured magnetic fields are mostly below the cutoffs used in other studies to separate high and low exposure (2 mG). One major advantage of so many measured values is a fairly reliable division of low-field from high-field residences; interestingly, the study reported by Preston-Martin et al. (85) does not find significant risk associated with either a high magnetic field (>2 mG) or a high wire code. Location is critical here as well. For example, 24-hour measurements are much more likely to be reasonable estimates of long-term (yearly) average exposure in a relatively nonseasonal climate such as Los Angeles than they are in Denver or Scandinavia.

Even if lines alone are important, the relative placement of three-phase conductors in a transmission line may lead to lower electric and magnetic field strengths near higher-current lines than lower-current ones. Moreover, those studies using proximity to electric power sources (usually overhead transmission lines and substations) frequently use 50–100 m as the cutoff distance dividing "exposed" from "unexposed" subjects, while field strengths may well reach background levels within 15 m of substations and lower-power transmission lines, depending on conductor arrangement. Both of these errors result in subjects being classified as "exposed" when in reality they are not.
and they can be avoided by using calculated field levels based on known load information. Therefore, such calculations are preferable to distance alone as an exposure metric. The calculation method is probably the best magnetic field measure to correlate with wire codes, if indeed the magnetic field aspect of wire codes is the biologically important factor in relation to cancer. Ideally, one would like to compare power load records over an extended period of time, perhaps 5 years, near and in subjects’ homes; unfortunately, such records are rarely available and difficult to interpret when present.

Another assessment problem is the documentation of an individual’s time at a particular job or residence. Few of the studies adequately record the duration of employment or time of residence relative to cancer diagnosis. For most of the cancers that we have examined, little if anything is known of the time required after initiation for the cancer to develop to a detectable stage. Although it is generally agreed that magnetic fields, if they have any carcinogenic effect, are promoters rather than initiators, the length of time needed for their action is unknown. It is important, therefore, to determine the length of time of any exposure prior to cancer diagnosis. Changes of job task should be assessed, as should changes of residence. Environmental studies are particularly vulnerable in this respect, as it is not known whether a person residing in a “high-magnetic field” home for 15–20 years before diagnosis should be placed in the same exposure group as someone residing in a “high-magnetic field” home for the 5 years immediately preceding diagnosis.

A related problem is accounting for duration of exposure from multiple sources. When field measurements have been made in workplaces (67, 71), values of mean and median are not that much greater than in a residential setting. To what extent might exceptional residential exposures be significant, even for workers in “high-field” occupations? On the other hand, exceptional occupational magnetic fields would seem to be important when comparing residential exposures. The types of exposures in the two environments may also be quite different, having varying proportions of long-term, relatively low fields and short-term, intense fields. Multiple exposures in the home (power lines, appliances, ground currents, and so on) are best assessed through measurement; wire code is insufficient.

The Swedish occupational data (71) are equivocal on the matter of the relative importance of mean, median, standard deviation, and time above a threshold in exposure assessment. For leukemia, similar results are found for all measures, while for brain cancer, median and threshold measures lead to a suggested association; mean and standard deviation do not. If the time above a threshold or the presence of transient components is important, localized in-home sources (appliances) may well be more critical than occupational sources in some cases. More studies examining several different exposure metrics are needed to determine the robustness of the results. Although significant associations with wire code or distance to a source support the idea that health effects are related to long-term, low-intensity exposures, laboratory work is needed to determine the relative importance of the various exposure metrics.

Evidence is also needed from laboratory studies of electric and magnetic fields as to what cancers are caused in laboratory animals when the exposure can be documented. This evidence is minimal today; although an excess of skin cancer has been shown in one study (89), a similar study found no effect (90). Suggestions of breast and brain cancer promotion are inconclusive at present (91, 92). Recent work on melatonin synthesis in rodents has begun to suggest a link between magnetic fields and breast cancer (93), but many more data are needed to confirm and quantify this tentative conclusion. Equivalent experimental evidence for causative associations between electric and magnetic fields and brain cancers and leukemias does not exist at present. No evidence exists that electric and magnetic fields are mutagenic, though they may be promoters or copromoters.

Though physical arguments have been used to dismiss any postulated harmful interaction between living tissues and magnetic fields (94), recent experimental discoveries (95, 96) reinforce the idea that tumors of the central nervous system (particularly the brain) are plausible. Magnetic fields can interact and possibly interfere with the normal operations of nervous tissues, especially those bearing magnetite crystals, though there are physical arguments against effects of weak magnetic fields even here (97). In addition, magnetic fields may interfere with hormonal regulation systems that may be related to certain cancers (98). Solid experimental evidence and dosimetry data are still lacking, however.

Data are needed on which organs are at highest risk and which harmonics of 50- to 60-Hz magnetic fields are most likely to cause the strongest effect. At present, neither a physical theory nor experimental evidence exists to predict or explain which organs are most affected by power-frequency fields, or which aspect of these fields (average magnitude, peak, duration above some threshold, higher-frequency harmonics, and so on) is most critical in determining biologic effect.

While this paper was in press, the results of a large childhood leukemia study were published (99, 100).
The authors report no significant association of acute lymphoblastic leukemia with magnetic fields, whether indirectly or directly measured. Notable improvements over previous work include a large population covering a wide geographic area, measurements in homes within 2 years of cancer diagnosis, and wire coding of all subjects' homes even if in-home access was not possible or (in the case of potential controls) if subjects refused participation. The wire-coding methodology in particular is excellent and strongly suggests that wire codes are not associated with childhood leukemia. However, the paper raises two major methodological questions. 1) A 24-hour bedroom measurement may not be adequate for an annual average in the current or previous year. No information is presented on adjustment for seasonal variation (appreciable in the midwestern and eastern states studied). 2) Because magnetic fields cannot initiate cancers but, if they have any effect, must act as promoters, only initiated children would be expected to show an association with magnetic fields. Such sensitive populations could have been exposed to significant levels of chemical or physical agents or be genetically susceptible to cancer-causing agents. With the exception of excluding subjects with Down's syndrome, such information is not provided in this paper.

CONCLUSION

For neither cancers of the central nervous system nor leukemias can we conclude at this time that strong evidence exists for an association with electric and magnetic fields in the occupational setting. Studies of environmental exposure to electric and magnetic fields and cancer show weak evidence for an association of electric and magnetic fields with childhood leukemia and possibly childhood brain cancer. The most recent studies do not add support to the brain cancer link (85) and weaken the leukemia link (99, 100). Among adults, the environmental studies do not confirm the weak evidence from occupational studies for adult leukemia, and there are insufficient data for adult brain cancer. If epidemiologic knowledge is to advance in this area, scientists must put special effort into more accurate ways of assessing exposure. Continued reliance on only short-term (24-hour) measurement for a single day and/or external wire coding will not add to our understanding.

In the design of future studies, scientists should concentrate on improving exposure assessment and accounting for various confounders. Specifically, environmental studies of adults should include occupational exposure, and occupational studies should include environmental (home and travel) exposures. This is most easily accomplished with the use of a portable monitor attached to the subject (case, control, or surrogate), in conjunction with an activity diary or estimate of time spent in different activities. Similar monitoring of children should also be attempted in order to include exposures from school, day care, and so on. It is difficult to see how a biologic system might retain any "memory" of previous exposure to electric and magnetic fields; therefore, questions of a mother's activities while pregnant with a child subject are relevant, while the father's activities during that same time are not. In most seasonal climates, 1 day's monitoring of environmental exposure to electric and magnetic fields is very likely insufficient; at the least, 1 day of data at typical temperatures per season should be collected. Much preferred would be 1 month/season. Even in the United States where long-term power consumption records are not maintained, most utilities have 1 year's data on electricity consumption that could and should be utilized in determining the contribution of powerline fields to individual exposures.

Finally, data on other risk factors should be gathered, including exposure to carcinogenic chemicals such as benzene and to ionizing radiation (including diagnostic x-rays) at work and at home.

New occupational studies using job titles alone or primarily and new environmental studies using only wire coding and/or 24-hour metering of homes are unlikely to add to the present body of knowledge. Answers to the question of electric and magnetic fields as a cancer promoter or copromoter will require extensive, careful case-control studies using the most valid means of exposure assessment.

ACKNOWLEDGMENTS

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REFERENCES

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