Electric and Magnetic Fields (EMFs)

Introduction

Electromagnetic fields (EMFs) are invisible lines of force that surround any electrical device and are produced by the generation, transmission, and use of electric power. Electric fields are produced by voltage, while magnetic fields result from the flow of current through wires or electrical devices.[1] Interest in magnetic fields and breast cancer was initially sparked by reports of elevated breast cancer rates among men working in electrical occupations.[2-5] In addition, Stevens presented a hypothesis proposing that magnetic fields could suppress melatonin levels in the same way as light at night, thereby inhibiting a protective effect of melatonin on breast cancer risk.[6] These reports, in conjunction with ubiquitous magnetic field exposures in industrialized areas where breast cancer rates tend to be elevated, have led to a great deal of interest in the potential role of magnetic fields in breast cancer etiology. Despite considerable research over the last few decades, no consistent evidence, either experimental or epidemiologic, has emerged to support an association between magnetic fields and breast cancer. In addition, experimental research has not been able to consistently confirm the ability of magnetic fields to suppress melatonin production, as was suggested by some early studies. These results undermine support for a plausible mechanistic pathway by which EMFs could exert an etiologic effect.

Concept/Exposure Definition

The term EMF encompasses two distinct exposure fields – magnetic fields and electric fields, both of which are created by the generation, transmission and use of electric power. Because electricity is pervasive in our environment, so are EMF exposures. In the workplace, sources of EMF exposures include: electronic office equipment such as computers, fax and copy machines, scanners, and printers; fluorescent lights; security systems; and any kind of power tools, such as saws, sewing machines, and welding equipment.[1, 7] In the home, electrical appliances such as electric blankets, hairdryers, microwave ovens, electric shavers, air conditioners, electric heaters, television sets, vacuum cleaners, and toasters all generate EMFs.[1, 7] In addition to electronic and electrical equipment, the internal electrical wiring, meters, service panels, and grounding systems in a home or workplace also generate EMFs. Sources of EMFs exist outside of the residence or workplace and include high-voltage power lines, distribution lines, underground cables, substations, transformers, and transportation systems.[7]

The strength of both magnetic and electric fields decreases rapidly with increasing distance from the source.[1] Electric fields are easily shielded by materials that conduct electricity, even poor conductors such as trees, buildings, and skin. Magnetic fields, however, are not easily shielded and can penetrate buildings and human skin.[1, 8] Since magnetic fields are more likely to penetrate the body than are electric fields, most cancer research has focused on the magnetic component of EMFs.

Electric fields are produced by voltage and thus are only created from an appliance when the power is turned on. Since voltage in power lines typically doesn’t change much, the electric fields from power lines are relatively stable.[1] Magnetic fields, however, are created from the flow of electric current. Thus, magnetic fields from appliances are only generated when the power is turned on. Magnetic fields from power lines can fluctuate greatly as current changes in response to changing electrical loads.[1] Although magnetic fields near many electrical appliances are higher than near power lines, appliances contribute less to a person's total exposure to magnetic fields, because appliances are typically only used for short periods of time and not often used close to the body.[8] Furthermore, the magnetic field strength decreases more rapidly from point sources, such as appliances, than from power lines. Given the multiple potential sources and transient nature of magnetic field exposures, characterization of exposure is complex and challenging.

Because magnetic field exposures are imperceptible, they do not lend themselves to self-report. In most of the epidemiologic studies of cancer and magnetic fields conducted to date, crude proxy measures of exposure have been used. Occupational sources of magnetic fields have been based on job classifications, with or without supplemental field measurements. Residential sources of magnetic fields typically have been characterized by proximity to electric/transmission sites, self-reports of household appliance use, and/or estimated by characteristics of power lines outside of the home (i.e. wire codes or calculations of magnetic field levels generated by the power lines).

The development of fairly sophisticated magnetic field monitors in recent years has improved understanding of exposure in different occupations and in homes. A remaining limitation in assessing magnetic field exposures for a breast cancer study, however, is the lack of knowledge as to which attribute of exposure (e.g., frequency, intensity, peak, variations, etc.) is likely to be most biologically relevant.

Biologic Rationale/Mechanism

The leading biologic mechanism that has been explored with respect to magnetic field exposures and breast cancer is the melatonin hypothesis. In 1987, Stevens and colleagues first suggested that magnetic fields might increase breast cancer risk by suppressing melatonin output.[6] Initially, it was thought that decreases in melatonin would lead to increases in estrogen levels that would then increase breast cancer risk.[6] Other mechanisms mediated by melatonin also have been suggested, including a suppression of breast cancer by a melatonin-mediated boost in immune function and by direct suppression of breast cancer cell growth.[7] While substantial evidence now exists for a protective role of melatonin in breast carcinogenesis (see Section I, Chapter H, Light at Night), the evidence that magnetic fields can affect melatonin levels is, at best, equivocal.

Despite considerable research aimed at assessing magnetic fields' effect on melatonin levels, the evidence is inconsistent.[1, 7, 9-12] Among at least 60 laboratory animal studies, some have shown a suppression of melatonin associated with magnetic field exposures, while others have not. However, two interesting human breast cancer cell line studies showed that environmentally relevant magnetic fields interfered with melatonin's oncostatic action on MCF7.[13, 14]

Clinical studies of human volunteers exposed to EMFs in a controlled environment have reported no effect of magnetic fields on melatonin levels. Some studies of people exposed to magnetic fields at home or in their workplace have reported small reductions in melatonin levels, but these findings are difficult to interpret for several reasons. The effect has generally been confined to subgroups and the characteristics of the people in the subgroups in which effects were observed have varied between studies.[15-18] In addition, because there is no control for other factors that might affect melatonin levels in such studies, we don't know whether the melatonin reductions are due to magnetic fields, some other environmental or behavioral factor, or occupational exposure.[1, 7] The fact that similar reductions are not seen in the controlled clinical studies supports the supposition that some other exposure is the responsible agent. A few of these studies have suggested that magnetic fields' ability to suppress melatonin production may be limited to subgroups of women using exogenous estrogens or other prescription drugs,[15, 16] a possibility that, if confirmed, would be important.

A multitude of laboratory studies have been conducted to evaluate other potential mechanistic pathways for magnetic fields' potential carcinogenic effects outside of the melatonin pathway. Over 1,000 studies have sought to identify cellular effects associated with EMF exposures, including changes in cell proliferation and differentiation, gene expression, enzyme activity, and DNA damage. In its 2000 report of the health effects of EMFs, NIEHS reviewed this body of literature and concluded that there is "little convincing evidence of cellular effects of EMFs at environmental levels."[1] Furthermore, the NIEHS reported that most evidence to date "suggests EMF is not genotoxic."[1] The few studies that have reported evidence of genotoxicity have not been replicated. Given the lack of evidence for any direct genotoxic effect, some investigators have focused on multistage carcinogenesis studies in rodents to assess whether EMFs exert promotional effects on breast carcinogenesis after genetic damage has been induced by known carcinogens such as UV light, by chemical carcinogens, by radiation, or in mice genetically pre-disposed to mammary tumors. While the data are still sparse and results fairly mixed, some of these studies have suggested a cancer-promoting effect of EMFs.[1, 10] In an intriguing example of possible interactions between EMFs and other exposures, Loscher and colleagues in Germany (e.g., Mevissen et al. 1996;[19] Thun-Battersby et al. 1999[20]) have consistently reported that exposure to an environmentally-relevant magnetic field increases chemically-induced mammary tumor formation in rats. This result was not replicated by two other labs,[21, 22] but the choice of rat strain may be the difference.[23, 24] Little or no further work has been conducted in the U.S. on this potentially important science.

In summary, the biologic evidence to date of a mechanism for magnetic field exposures inducing breast carcinogenesis is weak. While the 'melatonin hypothesis' initially provided a theoretic framework for a potential effect, laboratory research generally has not supported this hypothesis. Melatonin levels in humans do not appear to be affected by magnetic field exposures. There is substantial evidence that magnetic fields are not genotoxic and no physiologic effects at the cellular level consistent with tumor initiation have been consistently identified. There is some evidence that magnetic fields could play a role in cancer promotion or interact in some way with other exposures, but so far that evidence is limited.

Review of the Epidemiologic Literature

In the last five years, a number of national and international agencies have reviewed the literature on the health effects of magnetic field exposures and published reports summarizing their findings.[1, 10, 25] Additionally, a number of review articles have appeared in the peer-reviewed scientific literature discussed below.

As part of the state of California EMF Program's review of the literature, Erren and colleagues conducted a meta-analysis of magnetic fields and breast cancer, including all relevant studies published through January 2000.[11] Risk estimates from the 24 studies that reported on breast cancer and magnetic fields in women ranged from 0.6 to 1.64, with a pooled estimate of 1.12 (95% CI = 1.09–1.15). There was, however, substantial heterogeneity of results, with 14 studies reporting relative risks between 0.9–1.2, five reporting risk estimates below 1.0, and five reporting risk estimates greater than 1.35. Sample sizes tended to be small and confidence intervals wide, with only five of the 24 studies yielding confidence intervals that did not include one. There was significant heterogeneity in results, such that variations in findings between studies were greater than those expected by chance (*p* value = 0.035). Thus, despite the significantly elevated pooled estimate of risk, the author stated that "it is premature to conclude that the observations reflect a real, rather than an artifactual association," citing the lack of consistency in study findings, doubts that differing indices of exposure really capture the same phenomenon, and concerns about inadequate covariate adjustment.[11]

This conclusion has been echoed by all the major reviews conducted to date.[1, 7, 10, 11, 25, 25-28] While lack of experimental evidence to support the hypothesized biological mechanism (as discussed previously) is central to the conclusions made in these reviews, the lack of consistent epidemiologic evidence is also cited. The primary limitations in the epidemiologic studies include: incomplete or indirect exposure assessment; limited ability to control for confounding factors; and small numbers of cases. Epidemiologic investigations of magnetic fields and breast cancer have tended to focus either on occupational or residential sources of exposure. Only two studies to date have incorporated exposures across both the home and workplace.[29, 30]

Since the publication of the large-scale reviews by IARC, NIEHS, and the California Department of Health Services (which included the meta-analysis by Erren), a number of additional epidemiologic studies of magnetic fields and breast cancer have been published. While these more recent studies tend to have more comprehensive exposure assessment methods, they continue to generate inconsistent, but generally null, findings. Six of these studies have focused on residential exposures[30-35] and most have vastly improved on the exposure measures of the earlier studies.

The first of these, a case-control study conducted in Seattle and published in 2002 by Davis and colleagues, used several different metrics of magnetic field exposure, including survey data to collect information on household electrical appliance use, nighttime spot measurements of magnetic fields in subjects' bedrooms in the home in which they lived at the time of study enrollment, and wire coding of current and all residences within the previous ten years.[32] None of these exposure measures was significantly related to breast cancer, either in the whole study sample or among subgroups of interest (e.g., defined by tumor estrogen receptor status, menopausal status). The odds ratio for the highest quartile of mean nighttime magnetic field measurements in the bedroom was 0.9 (95% CI = 0.7–1.3); for highest quartile of estimated exposure based on wire codes was 0.8 (95% CI = 0.5–1.3); and for highest quartile of estimated exposure based on appliance use was 1.1 (95% CI = 0.8–1.5).

A later analysis of data from the Multiethnic Cohort in Los Angeles used a similar approach, collecting both measured nighttime magnetic field values in subjects' homes at study entry, as well as wire coding for every residence during the previous ten years.[31] Similar to the Seattle study, no significant findings were reported for either of these magnetic field exposure metrics with an odds ratio of 0.76 (95% CI = 0.49–1.18) for the highest exposure category based on wire configuration and an odds ratio of 1.31 (95% CI = 0.82–2.09) for the highest quartile of mean measured nighttime magnetic field levels.[31]

While the exposure assessment in these studies is improved over earlier studies, no 'perfect' metric has been utilized. The magnetic field measurements probably better capture actual personal exposures experienced during nighttime (the most biologically relevant time if melatonin is the mechanistic pathway), but they are limited in that they cannot estimate prior exposures. Conversely, the wire coding estimations were calculated for ten-year periods, but the degree to which they reflect actual personal exposures of subjects is not known. In fact, Davis et al. reported that in their study, the wire codes of the current house did not correspond well to the measured values in the home (Spearman Rank correlation coefficient = 0.26; $p < 0.001$).[32]

In a similar study of magnetic fields and breast cancer conducted on Long Island, NY, researchers also collected a plethora of exposure data, including survey information on electric appliance use, both spot and 24-hour magnetic field measurements at various locations in the home, as well as estimated exposure based on wire codes.[34] A previous analysis of the exposure data used in this study demonstrated a high degree of correlation between 24-hour measurements and estimations based on wire codes.[36] Furthermore, this study had the added advantage of being limited to a population of women who had lived at their current residence for at least 15 years. Thus, the measured values in the home at study entry are likely to capture historical exposures, at least to the degree to which measured values of magnetic fields have not changed for a given residence over time. This study's results were also null. The odds ratio for the highest estimated exposure from wire codes was 0.90 (95% CI = 0.54–1.48); the odds ratio for the highest quartile of 24-hour magnetic field measurements was 0.97 (95% CI = 0.69–1.37) in the bedroom and 1.09 (95% CI = 0.78–1.51) in the most lived-in room.

In contrast, a population-based study coming out of Norway recently reported a nearly 60 percent increase in risk of breast cancer associated with residential magnetic field exposures estimated as fields generated by nearby high-voltage power lines (OR = 1.58, 95% CI = 1.30–1.92), although no consistent dose-response pattern was found.[30] Magnetic field exposures were estimated for all residences during the follow-up period (minimum of 13 years) and were expressed as the time-weighted average across all residences. These associations were seen in women with both ER+ and ER- tumors and among both pre- and post-menopausal women. While the strength of this study is its ability to estimate historical residential exposures from high-voltage lines, it is limited by its inability to incorporate information on other sources of residential magnetic field exposures and its lack of measured values of exposure. The authors do note that a previous Norwegian study using similar exposure assessment techniques showed that the magnetic fields from power lines were the major source of exposure among children living close to a power line.[37]

Two other recent studies examined the risk of electric blanket/bedding devices and breast cancer risk, one reporting an association (OR = 4.9, 95% CI = 1.5–15.6 for ≥ 10 years of usage)[35]and one reporting a statistically non-significant increased risk in pre-menopausal, but not post-menopausal, women (OR = 1.4, 95% CI = 0.7–2.6 in pre-menopausal women and OR = 0.8, 95% CI = 0.5–1.3 in post-menopausal women with ≥ 10 years of usage).[33] Reasons for the disparate findings are not immediately apparent but are in keeping with the inconsistent findings of previous studies published on this exposure, some of which have reported an effect,[38, 39] while others have not.[40-43] The authors of the recent positive study,[35] which was conducted among African Americans, note that their findings are consistent with two previous studies on occupational magnetic field exposures involving African American women, which found a stronger association between exposure and breast cancer in African American women than in Caucasian women.[44, 45] The authors of the recent study speculate that African American women may be more susceptible to magnetic field exposures.[35] It is worth noting, however, that the magnetic field analysis in the L.A. Multiethnic Cohort by London and colleagues did not see an effect in any racial/ethnic group, including African Americans.[31]

Five additional studies of occupational magnetic field exposures and breast cancer recently have been published.[46-50] These studies generally addressed a number of the limitations cited in the reviews by IARC and others, including better control for confounding, more refined exposure assessment methods, and evaluating risks in subgroups that may be more susceptible to magnetic field effects.

In a population-based case control study from the U.S.,[50] magnetic field exposures were assessed using a combination of job titles and measured magnetic fields to estimate occupational exposures for six broad categories of occupation. Approximately 200 study volunteers wore personal magnetic field monitors and filled out a questionnaire about occupation. Cumulative measures of exposures were then estimated for all study participants, based on the two longest-held jobs. The association for cumulative occupational magnetic field exposures was not statistically significant (OR = 1.2, 95% CI = 0.8–1.7 for the 90th percentiles versus 30th percentiles of exposure).[50]

In a Swedish study that included 20,400 breast cancer cases identified from the population registry, researchers linked study participants' occupational histories to a new job-exposure matrix specifically designed to estimate magnetic fields in occupations common to women (previous job-exposure matrices had been developed only for men). The job-exposure matrix was created by measuring magnetic field exposures in 49 of the most common jobs held by women, covering approximately 85 percent of women employed in Stockholm. This study reported that all risk estimates examined, regardless of the choice of cut-points or exposure parameters, were close to unity, with an overall odds ratio of 1.01 (95% CI = 0.93–1.10) for women exposed to 0.30+ μT.[49] The large size of this study allowed for good precision in subgroup analyses.

In contrast, three recent studies reported an excess of breast cancer associated with occupational magnetic field exposures.[46-48] In a case-control study nested within a cohort of Norwegian female radio and telegraph operators, exposure estimates were based on years and workload according to ship type, an assessment that could not separate exposure to extremely low frequency magnetic fields from radiofrequency fields or light at night.[48] The study reported a statistically significant trend of increased breast cancer risk with increasing cumulative exposure. Stratified analyses showed an increased risk of estrogen-receptor-positive breast cancer in women under age 50, while the older age group had an elevated risk of estrogen-receptor-negative breast cancer.[48] The other two studies, one a hospital-based case-control study conducted in Canada,[47] and the other a U.S. population-based case-control study,[46] used occupational surveys reviewed by industrial hygienists to assign exposure categories. The U.S. study, which included over 6,200 cases and nearly 7,400 controls, reported a modest increase in risk compared to background levels that ranged from 1.06 in the lowest-EMF-exposure category to 1.16 in the highest category. While point estimates for each exposure level did not achieve statistical significance, there was evidence for increasing risk with increasing exposure (p value for trend = 0.03). A number of specific job titles were also evaluated. Data entry clerks were the only group to have a statistically significant increased risk (OR = 1.47; 95% CI = 1.06–2.04).[46] The Canadian study, which was limited to post-menopausal women, found an elevated risk associated with lifetime occupational exposures to magnetic fields in women who were exposed before the age of 35 among cases with progesterone-receptor-positive tumors. A similar, although not statistically significant, risk was found for estrogen-receptor-positive tumors. Most of the highly exposed women in the Canadian study were sewing machine operators and textile workers.

Overall, the epidemiologic evidence generally does not support an association between magnetic field exposures and risk of breast cancer. Early studies on this topic were limited by small numbers, crude measures of magnetic fields, incomplete control for confounders, and inability to evaluate risks in potentially susceptible subgroups. Later studies have generally addressed these limitations with much larger sample sizes, more comprehensive measures of magnetic field exposures (incorporating some actual measurements), control for most known risk factors for breast cancer, and subgroup analyses. These later studies continue to provide equivocal results. The evidence for an association between breast cancer and residential exposures is particularly weak. Studies that have examined risks in particular subgroups have reported excess risks in some subgroups, but not in the same subgroups across studies.[26] This suggests these may be chance findings.

Occupational studies have provided some slightly more provocative findings, although in these studies, too, occasional positive findings are often confined to subgroups within the studies. Furthermore, these studies generally suffer from the inability to consider other occupational exposures of potential importance. One such exposure of intense recent interest is light at night, which has been hypothesized to operate via melatonin suppression, and has been shown much more convincingly to affect melatonin levels than EMFs (see Section I, Chapter H, Light at Night).

Conclusions and Future Directions

Overall, there is a lack of evidence for an association between magnetic field exposures and breast cancer etiology in women. The lack of evidence is not from lack of effort. Hundreds of studies, both experimental and epidemiologic, have been conducted to evaluate this association. While the earlier studies suffered from major limitations, later studies—with large sample sizes, improved exposure assessment, and sufficient statistical power—do not provide evidence of association. A new insight into mechanism, a new exposure assessment strategy, or the identification of a different group of highly-exposed women for study would likely be needed to change the balance of evidence in this field.

Further epidemiologic evaluations of residential EMF exposures are especially unlikely to be fruitful. Exposure levels in the home are typically much lower than are those experienced in occupational settings and are difficult to estimate retrospectively.

Occupational studies also are difficult, given that, historically, few women have been employed in occupations known to have high levels of EMF exposures. Recent efforts have been made to identify high-EMF occupations dominated by women and to characterize EMF exposures in those occupations. Female-dominated occupations with high EMF exposures recently identified in a large occupational exposure study among Swedish women included: cashiers, working proprietors in retail trade, flight attendants, dental nurses, cooks, post-office clerks and kitchen maids.[51] Additionally, seamstresses, (who typically do not work in the garment industry in Sweden), were not identified as highly exposed in this study. But seamstresses have been reported to have some of the highest EMF occupational exposures among female workers in other studies.[52] If an interest in EMFs persists, a focus on the occupations posing the greatest potential exposures to EMFs among women may be warranted. Studies within these high-exposure occupations, utilizing measured EMF levels, and controlling for other occupational exposures, may prove worthwhile.

Ultimately though, the ability of epidemiologic studies to detect EMF-related breast cancer risks hinges on the ability to better elucidate the etiologic framework by which EMFs could affect breast cancer risk, so that exposure measurements are relevant to a biological mechanism. The biggest limitation of most epidemiologic studies to date has been inadequate exposure assessment. With the development of hand-held EMF exposure monitors, this limitation is no longer about instrumentation but about knowledge. We still do not know what attribute of magnetic field exposures might be most etiologically relevant. As Dr. Feychting notes in her 2005 review of the literature, the "absence of a clearly elucidated, robust, and reproducible mechanism of interaction of EMFs with biological systems deprives epidemiologic studies of focus in their measurement strategies."[28] Thus, substantial misclassification of exposure in epidemiologic studies is likely. Given the large body of experimental data that has not yet been able to identify a plausible biologic mechanism by which EMFs could affect breast cancer, new evidence of an underlying biologic mechanism should precede future epidemiologic investigation.

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