Nonionizing Radiation

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W. Gregory Lotz, PhD

The term *nonionizing radiation* designates a wide spectrum of electromagnetic radiation frequencies, from 0 Hz to over 10^{15} Hz (Fig. 84.1). The characteristics of energy transfer to the body and, therefore, the potential health effects of such exposure vary widely over this spectrum. Several types of nonionizing radiation have been the subject of considerable public attention and controversy in recent years. This chapter reviews the research literature concerning various types of nonionizing radiation to provide a perspective on the environmental and occupational exposures and the potential or perceived risks. Some of the main experimental findings are briefly summarized (although this literature is too extensive to describe comprehensively), after which the principal epidemiologic studies are reviewed, as these often drive public perception and risk estimates. Because this review provides little coverage of industrial hygiene, dosimetry, engineering, and basic biophysical aspects of these radiations, references are given to other sources that provide such information. The types of nonionizing radiation reviewed in this chapter include static and extremely low frequency (ELF) electromagnetic fields (EMF), and radiofrequency (RF) and microwave radiation.

EXTREMELY LOW FREQUENCY ELECTROMAGNETIC FIELDS

ELF-EMFs are usually defined to include 3 to 3,000 Hz, but the frequencies of most interest are the 50- to 60-Hz fields associated with alternating currents in electric power systems. Electric distribution in North America uses 60 Hz, while Europe and most of the rest of the world use 50 Hz. In the ELF range, the electric and magnetic fields are considered to be separate, nonradiating fields that are not coupled as they are for higher frequencies. Thus, discussions of the biological effects of ELF fields are separated into those related to electric field exposure and those related to magnetic field exposure. Electric fields are measured in volts per meter (V/m), while magnetic fields are measured in Tesla or Gauss (1 Tesla = 10,000 Gauss). For fields of interest in most environmental and occupational situations, the magnetic field is scaled to microTesla (μT) or milligauss (mG) (1 μT = 10 mG), and for that reason both will be used in this chapter. Even though electrical equipment and systems produce both ELF electric and magnetic fields, the interest in potential health effects has been greatest for magnetic fields. The interest in magnetic fields is related to the fact that magnetic fields penetrate the body unabated (while electric fields generally do not), and because some epidemiological studies have reported an increased cancer risk associated with exposure to magnetic fields. However, oscillating magnetic fields induce electric fields in body organs, so the biological effects from both fields should be considered in evaluating potential health hazards in the ELF range.

Everyone in the United States is exposed to some extent to ELF electric and magnetic fields produced by the generation, transmission, and use of electricity. The most common source of outdoor exposure is overhead electric transmission lines, which range in the voltage they carry from as low as 4 to 24 kV for distribution lines to as high as 765 kV for the largest transmission lines. The magnetic field under a maximally loaded 765-kV line may reach 10 or 20 μT (100 to 200 mG). EMF exposure in homes is usually dominated by the wiring of the house itself and by the electrical appliances in the home. In a study of 1,000 individuals, about 80% of the subjects had average magnetic field exposures under 0.2 μT (2 mG) (1). In a related study of nearly 1,000 homes, the mean magnetic field average for all homes was 0.09 μT, while half of the houses studied had magnetic field measurements of 0.06 μT or less (2,3).

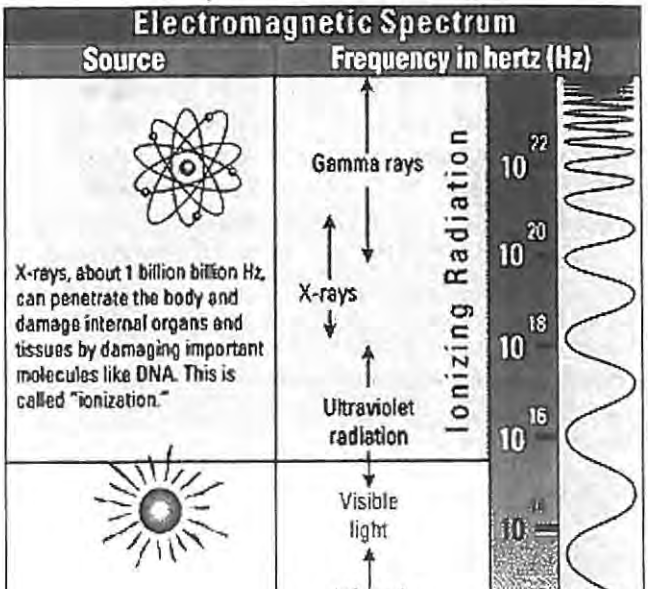

Figure 84.1 The spectrum of electromagnetic radiation frequencies.

Ranges of measured EMF exposures for a variety of home and occupational settings are shown in Figure 84.2. Measurements in offices have ranged from 0.1 μT (1 mG) to about 10 μT (100 mG). At the other extreme, workers near electrogalvanizing equipment or electric resistance heaters are exposed to magnetic fields up to 0.4 mT and 1.4 mT, respectively (4). The average EMF in homes is about 0.1 μT (1 mG), while the magnetic field can be up to 5 to 10 μT (50 to 100 mG) close to certain household appliances such as electric ranges, vacuum cleaners, hair dryers, food mixers, and shavers (3–6). The magnitude and range of EMF from power lines and household appliances are very different; for appliances the magnetic fields are confined mainly to a distance of a meter or two, whereas fields from high-voltage power lines have a range on the order of 50 to 150 meters (3).

Reviews of dosimetric, physical interaction, and biologic effects of EMF are found elsewhere (7–13).

Biologic Effects

For ELF fields, the individual photon energies are so low and the wavelengths are so long that the familiar mechanisms by which electromagnetic radiation changes molecules are ineffective. In spite of the lack of an obvious mechanism of action, results of same in vitro experiments suggest that EMF exposures have the potential to affect cell function in a variety of ways (11,14):

- Modulation of ion and protein flow across the cell membrane (e.g., calcium homeostasis)
- Alterations in gene expression and DNA repair
- Interaction with the cell response to different hormones and enzymes, including those involved in cell growth processes and stress responses (e.g., heat shock proteins)
- Intracellular signaling
- Interaction with the immune response of cells

It is difficult to interpret if these in vitro effects have any health significance. There is the normal difficulty of extrapolating in vitro findings to potential health outcomes. In addition, the in vitro effects generally have been observed only at magnetic field levels above 100 μT (1,000 mG) and electric fields above 1 mV per m (which can be induced in parts of the human body by 60 Hz magnetic fields as low as 15 μT). Changes in specific endpoints have been inconsistent, either in the direction or nature of change, or in the ability to observe the changes in similar experiments, sometimes even in the same laboratory. Some attempts at replication have been unsuccessful, yet new reports of such changes continue to appear (15). As a result of these factors, observed cellular effects are hypothesized to be a result of alterations in molecular or cellular interactions such as those that involve the complex processes associated with the cell membrane, including ion transport, immune function, and cell–cell communication.

Reproductive and Teratogenic Effects

A number of studies have used chick embryos to investigate the potential for ELF magnetic fields to cause teratogenic effects. While some studies reported developmental defects, other studies did not find any effects, and the overall results have been equivocal (16,17). Studies of reproductive and teratogenic effects in other animal models have, for the most part, been negative (11).

There have been a number of studies of human reproductive outcomes of EMF exposure resulting from work with video display terminals (VDT). As a whole, these

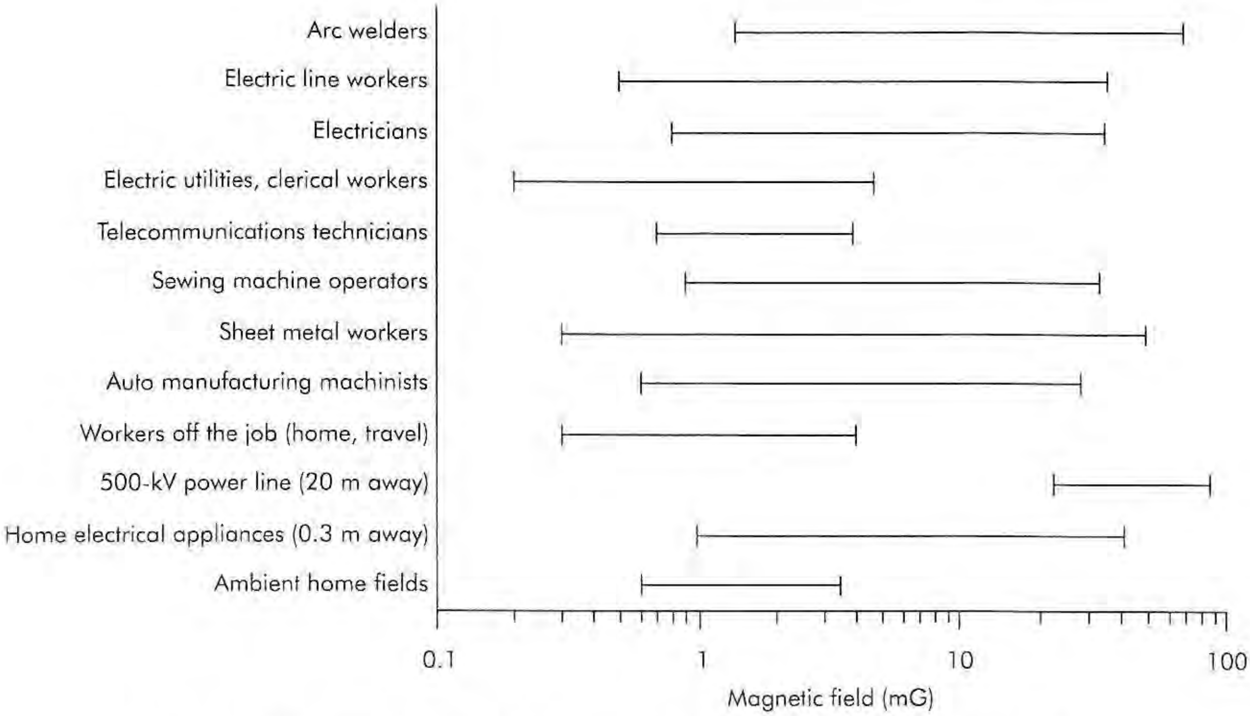

Figure 84.2 Ranges of measured EMF exposures in milligauss for a variety of occupational and home settings or electric power transmission line proximity. Values shown for occupational settings are the range of the workday averages for 90% of workers studied. Spot measurements for the same situations would cover a wider range. (From National Institute of Environmental Health Sciences. *EMF: electric and magnetic fields associated with the use of electric power: questions and answers*. NIH publication 02-4493. Research Triangle Park, NC: National Institutes of Health, National Institute of Environmental Health Sciences; 2002 with permission.)

studies do not indicate a strong association between the use of VDTs at work and the risk of a pregnancy ending in spontaneous abortion or congenital abnormalities. Two of the strongest studies, however, had differing conclusions. In one that focused on the very low frequency fields that are unique to VDTs (about 15 kHz), there was no difference in risk of spontaneous abortion or of reduced birth weight and preterm birth (18,19). In a study that involved workers using VDTs that had stronger magnetic field exposures, a threefold elevated risk for spontaneous abortions was observed (20). This elevated risk may have been due to the higher exposures, but the reason why this study found an elevated risk when most other studies did not is unclear. Other studies have looked at reproductive outcomes related to residential EMF exposure from the use of electrically heated beds (electric blankets, heated water beds). These studies were also equivocal, with a few reporting associations between exposure to electrically heated beds and adverse pregnancy outcomes, while other research did not find an association with EMF exposure (21–25). There have also been a few investigations of other types of occupational exposure with respect to reproductive outcome. In one of several studies evaluating the association between paternal exposure in electrical high voltage substations and adverse pregnancy outcome, Nordstrom et al. (26) reported an association between EMF exposures and congenital malformations in offspring. The authors hypothesized that the effect may have been related to the exposures to high voltage fields, but the study was limited by a small number of subjects and other methodological weaknesses noted by the authors, and other studies of workers in substations have not found similar associations (27–29). The EMF literature on reproductive and teratologic effects has been the subject of a number of reviews. One of the most extensive was by Brent et al. (30) and later reviews by Shaw (28) and an expert review panel (11) were all in agreement that the available data does not indicate a risk of adverse reproductive outcome at EMF exposure levels normally found in the environment.

Hematopoietic, Immune System, and Endocrine Effects

Many experimental studies, both in vitro and in vivo, have been conducted on the effects of EMF on various parameters of the hematopoietic and immune systems (14). The biological endpoints evaluated in these studies have varied widely and include erythrocyte indices, differential white blood cell counts, splenic lymphocyte subgroup analysis, lymphocyte proliferation, T-cell function, natural killer (NK) cell activity, antibody cell activity, and others. While some studies have reported changes in immune function, there were no observed differences in the overall health of the exposed animals from the sham-exposed group in these studies, leaving the significance of these limited changes in immune parameters uncertain (31,32). The overall picture that emerges from the body of literature for experimental studies of the hematologic and immunologic effects of ELF-EMF is that there are no detrimental effects related to exposures at levels normally encountered in the environmental or occupational arena (11,14).

Nordenson et al. (33) reported a high frequency of chromosome breaks in the lymphocytes of workers at an electrical substation and also found similar effects in the lymphocytes of train engine drivers, but the small numbers of subjects in these studies limit the conclusions that could be drawn (34). In addition, their findings were not supported by a different study of electrical substation workers (35). In general, there are too few studies of these endpoints in human subjects to draw any conclusions.

There have been many studies of melatonin in animals and humans because of its possible oncostatic and antioxidant effects and the potential link to the study of cancer in subjects exposed to EMF (36). The study of effect of EMF exposure on melatonin physiology was initially spurred by findings of melatonin suppression in rats exposed to electric fields (37,38). After over 2 decades of study of both electric and magnetic fields on the production and circulating levels of melatonin in various laboratory models, however, the evidence for an EMF effect on melatonin in animals is weak and inconsistent (11,14). When melatonin changes were observed, they were generally of suppression of melatonin production by the pineal gland or of circulating melatonin levels.

Several studies of melatonin in humans have reported changes in the urinary metabolite 6-hydroxymelatonin sulfate (6-OHMS) associated with exposure to EMFs. Burch et al. (39–41) have observed a decrease in 6-OHMS in three different groups of utility workers under certain exposure conditions. A similar effect, the reduction of nighttime excretion of 6-OHMS, was observed in railway workers in Finland (42). In a residential study that is perhaps the most rigorous study of melatonin in humans in terms of exposure assessment and control for confounders, total nighttime urine concentrations of 6-OHMS decreased in association with increasing levels of magnetic field strength in women's bedrooms but were not associated with personal magnetic field exposures over the same 72-hour period. This effect was primarily seen in women who used certain medications, such as beta blockers, calcium-channel blockers, and psychotropic drugs (43).

In a number of animal studies conducted to investigate other endocrine responses to EMF exposure (e.g., pituitary, thyroid, and adrenal responses), nearly all reported no difference between the exposed and sham-exposed animals.

Neurologic and Behavioral Effects

It is well established that animals and humans can perceive strong electric fields, and the studies documenting this have been reviewed a number of times (11,44). This perception can be an aversive stimulus if the fields are strong enough. Some organisms such as migratory birds are also able to respond to static magnetic field cues from the earth's static magnetic field (14,45). Various experimental models of neurobehavioral function under EMF exposure have been studied, from in vitro preparations of nerve tissue to tests of electrophysiological response in animals and studies of behavior in various animal species (11,14).

Much of the early work that established transmembrane calcium transport as a topic of great interest in EMF studies was done with isolated nervous tissue (46). The actual studies of calcium efflux from chick brain tissue that were landmarks in the topic were inconsistent in their outcome, had unusual dose-response characteristics, and were heavily criticized. Nevertheless, the effect of EMF exposure on calcium ion transport in nervous tissue came to be recognized as an important topic in EMF research and extended to many other experimental models besides nerve tissue (47).

There have been a few studies of learning or cognition in EMF-exposed workers who have not shown effects of EMF exposure (29,48,49). Interest has been growing over the last decade in chronic neurodegenerative diseases such as Alzheimer's disease (AD) and amyotrophic lateral sclerosis (ALS) as potential outcomes for EMF exposure. Both the National Institute of Environmental Health Sciences (NIEHS) working group (1998) and the International Agency for Research on Cancer (IARC) review panel (2002) concluded that the existing studies showed an association between EMF exposure and AD or ALS in epidemiological studies (11,12). The IARC review added, however, that the evidence for the link between AD and EMF exposure was weak, as a result of the limited number of studies and methodological weaknesses in those studies. The evidence for the association between AD and EMF exposure has continued to accumulate since that review, with more recent studies of occupational exposure in a cohort of Swedish individuals and a specific community of individuals in Sweden (50,51). Ahlbom (52) noted in his review that he found the accumulated evidence to be actually stronger for ALS than for AD. The strength of this evidence comes from mortality studies of electric utility workers (53–55). In the populations, the significant associations between ALS and magnetic fields exposure are potentially confounded by associations with elelctric shocks. However, magnetic field associations with ALS and AD are reported by Park et al. (55a) in a population-based study of occupational exposures. In a study by Feychting et al. (50), ALS was not associated with EMF exposure, but an elevated risk of ALS in men with a history of what was referred to as "electrical and electronics work" was reported.

Although there are some studies that found a relation between EMF and suicide in workers whose job history indicated an exposure to EMF and others that observed an association between residential proximity to overhead power lines and depression, the overall evidence in the available literature for these health outcomes and EMF exposure is weak and inconsistent (12,14,52).

Electromagnetic Hypersensitivity

The term electromagnetic hypersensitivity (EHS) has come into use in the last decade and refers to a condition in persons who attribute subjective health symptoms to exposure to electromagnetic fields. This condition was first studied in Sweden more than 2 decades ago when complaints arose related to skin problems and VDT use (56). The reported symptoms included general complaints such as headache, fatigue, and weakness, and skin sensations including itching, tingling, and burning. A survey of 15,000 persons in Sweden suggested a prevalence of about 1.5% of the population for this self-reported condition, with the prevalence higher in women than in men (57). Symptoms can be very severe, even disabling, in some sufferers. Studies of EHS have been limited but include blinded laboratory provocation studies where self-reported EHS subjects were exposed to EMF and monitored for various endpoints during the study (58–60). While these blinded provocation studies have not been able to verify that EMF exposure can trigger the symptoms. In general, the studies of EHS suggest that these symptoms are not related to EMF exposure and the etiology of the health problems attributed to EHS remains to be identified (14,57,61–63).

Carcinogenic Effects

In 1979, Wertheimer and Leeper (64) reported that childhood cancers including leukemia, lymphoma, and nervous system tumors were associated with what the authors termed "residential high-current configurations (HCC)," which were defined by visible characteristics of the electric lines serving the house of the subject, such as the size of the wires and the proximity of the house to wires, transformers, and power stations. Over the decades since that initial report of an association between childhood leukemia and EMF exposure (or a surrogate of that exposure), both the quality and the quantity of epidemiologic studies of the EMF–cancer link has steadily increased. Among the additional studies, a larger, improved case–control study in the same city (Denver) as the initial study as well as numerous residential and occupational studies in many countries around the world (65). When an expert panel was convened in the United States in 1992 specifically to review the EMF data, it concluded that "there is no convincing evidence in the published literature to support the contention that exposures to extremely low-frequency electric and magnetic fields (ELF-EMF) generated by sources such as household appliances, video display terminals, and local power lines are demonstrable health hazards" (66). More specifically on the question of cancer, the panel reported that "epidemiologic findings of an association between electric and magnetic fields and childhood leukemia or other childhood or adult cancers are inconsistent and inconclusive. No plausible biological mechanism is presented that would explain causality" (66).

During the 1990s, there was strong interest in EMF research, and many studies were conducted, both in the laboratory and epidemiologically. A special supplemental program was funded by the U.S. Congress to conduct additional research and to evaluate the health effects of EMF produced through the generation, transmission, and use of electric power (67). This program was known as the EMF Research and Public Information Dissemination, Program (EMF RAPID). Public information documents were among the publications produced by the agencies that directed the program, the NIEHS and the Department of Energy (3,4). Even though the EMF RAPID Program did not fund any new epidemiological studies, many such studies of both occupational and residential exposure were being added to the literature during this time. In 1999, at the conclusion of the EMF RAPID Program, NIEHS reported to Congress that they had concluded that "the scientific evidence suggesting that ELF-EMF exposures pose any health risk is weak. The strongest evidence for health effects comes from associations observed in human populations with two forms of cancer: childhood leukemia and chronic lymphocytic leukemia in occupationally exposed adults" (10). NIEHS went on to report that "the epidemiological studies demonstrate, for some methods of measuring exposure, a fairly consistent pattern of a small, increased risk with increasing exposure" (10). The designation of "weak evidence" by NIEHS was based, in part, on the absence of clear supporting evidence for carcinogenicity in laboratory animal studies and the lack of a plausible biophysical mechanism that could explain the nature of the carcinogenic risk.

One of the activities conducted by NIEHS was the convening of a large international review panel to evaluate the scientific literature. This "working group," as it was called was one of several expert review groups to use the rating system for carcinogens used by the IARC. That rating system is:

- I – Carcinogenic to humans. This category is used when there is sufficient evidence of carcinogenicity in humans.

IIA – Probably carcinogenic. This category is used when there is limited evidence of carcinogenicity in humans and sufficient evidence of carcinogenicity in experimental animals.

IIB – Possibly carcinogenic. This category is used when there is limited evidence of carcinogenicity in humans and less-than-sufficient evidence of carcinogenicity in experimental animals.

III – Not classifiable. This category is used when the evidence of carcinogenicity is inadequate in humans and inadequate or limited in experimental animals.

IV – Probably not carcinogenic. This category is used when there is evidence suggesting a lack of carcinogenicity in humans and in experimental animals.

Table 84.1 shows the classifications given ELF-EMF by four of the review panels that have used the IARC rating system (11,12,68,69). The panels were in agreement about the classification of the evidence related to childhood leukemia but not in clear agreement for adult leukemia. They were mostly in agreement that the evidence is not adequate to classify with respect to adult brain cancer.

An example of the more thorough, well-designed epidemiological studies that have been added to the database on EMF and cancer was the study by Linet et al. (70) of the National Cancer Institute. In the study, with 638 cases and 620 controls, no association was reported between residential exposure to magnetic fields and acute lymphoblastic leukemia (ALL) in children. In the subjects' current and former homes, data collectors measured magnetic fields for 24 hours in each child's bedroom and for 30 seconds in three or four other rooms and outside the front door. A computer algorithm assigned wire-code categories, based on the distance and configuration of nearby power lines, to the subjects' main residences and to those where the family had lived during the mother's pregnancy. Magnetic fields were usually measured within 24 months after the date of diagnosis in the children with ALL. The odds ratio for ALL was 1.24 [95% confidence interval (CI), 0.86 to 1.79] at exposures of 0.200 μT or greater as compared with less than 0.065 μT. The risk of ALL was not increased among children whose main residences were in the highest wire-code category [odds ratio (OR)] as compared with the lowest category 0.88 (95% CI, 0.48 to 1.63). Lastly, the risk was not significantly associated with either residential magnetic-field levels or the wire codes of the homes mothers resided in when pregnant with the subjects (70).

While the individual epidemiologic studies present a mixed picture of positive and negative results, the strongest evidence considered by the later panels [IARC and National Radiological Protection Board (NRPB)] were two pooled analyses of the original data from a number of studies (71,72). Even with strong individual studies like that of Linet et al. (70) when working with the data from all the available studies, the authors of the pooled analyses found that (a) chance could account for the apparent inconsistencies between the original findings, (b) the dose-response was significant, and (c) categorical odds ratios of two were significant in homes with long-term average ELF magnetic fields above 0.3 μT (3.0 mG) or 0.4 μT (4.0 mG) (71,72). It was this kind of synthesis that contributed to the determination of the later panels (shown in Table 84.1) that ELF-EMF is a possible carcinogen. The results of a recent study in Japan are consistent with the findings of the pooled analyses, confirming the association between childhood leukemia and EMF exposure (72a).

The occupational cancer results from the ELF studies do not have the level of agreement that exists among the reviews of the childhood leukemia data. Individual studies provide inconsistent results for both leukemia and brain cancer. No pooled analysis has been published of all these data. Meta-analyses have been done that showed weak positive associations for leukemia and brain cancer, but these analyses did not distinguish

Table 84.1

Conclusions of Extremely Low Frequency Electromagnetic Fields Risk Evaluations

Panel	Childhood Leukemia	Adult Leukemia	Adult Brain Cancer
Swedish National Board of Health and Welfare (1995)	Possible (IIB)	Possible (IIB)	Possible for some electric jobs
NIEHS Working Group (1998)	Possible (IIB)	Possible (IIB)	Inadequate
NRPB Advisory Group (2001)	Possible	Inadequate	Inadequate
IARC (2001)	Possible (IIB)	Inadequate	Inadequate

IIB, possibly carcinogenic; NIEHS, National Institute of Environmental Health Sciences; NRPB, National Radiological Protection Board; IARC, International Agency for Research on Cancer.

between the studies that assessed exposure through personal monitoring from those that assumed some group of "electrical" workers were exposed (73,74). The best available synthesis of occupational cancer data is a comparative study of four studies of electric utility workers (75). These four studies were all nested case–control studies that used job-exposure matrices assembled from full-shift personal monitoring (76–79). This comparative study had original data from all but one of the individual data sets, which they analyzed by a common protocol for comparison and pooling. However, they could only pool published results for the last utility (78).

As with childhood leukemia, the comparative study of the electric utility data found that the apparent differences between its component studies were not significant and likely due to chance. The odds ratios in the highest exposure group (cumulative exposures $\geq$16 μT-years) were 1.87 (95% CI = 1.17 to 2.98) for brain cancer and 1.48 (95% CI = 0.96 to 2.30) for leukemia. The exposure–response slopes were OR per 10 μT = 1.12 (95% CI = 0.98 to 1.28) for brain cancer and 1.09 (95% CI = 0.98 to 1.21) for leukemia.

The number of epidemiological studies has decreased in the past 5 years, as interest in RF radiation studies has grown. There is widespread agreement that a better understanding is needed of what exposure metric should be measured for improved exposure assessment before further epidemiological studies have a good probability of clarifying the risk. The focus of strategies for new research is now on the search for a biophysical mechanism to understand the biological effects observed with low-level magnetic fields and to identify the biologically appropriate metric to be measuring in future studies.

MAGNETIC RESONANCE IMAGING AND OTHER STATIC MAGNETIC FIELDS

The static (0 Hz) magnetic field of the earth, to which humans are constantly exposed, averages about 50 μT (0.5 G) and ranges from 35 to 70 μT depending on the latitude, with the highest fields being at the poles (12,80). The earth's magnetic field intensity also varies over this range in man-made structures, depending on the presence of ferromagnetic materials (e.g., steel) in the vicinity of the measurement. Strong static magnetic fields are found in some occupational settings, such as the aluminum industry, arc-welding processes, and certain railway systems. A few industrial processes (e.g., electric welding machines, electroplating and other electrochemical processes) can subject workers to static magnetic fields of up to 10 mT (100 G), while magnetic resonance imaging (MRI) systems may expose patients as much as 4 T (40,000 G). Reviews of studies of the bioeffects of MRI and static magnetic fields may be found elsewhere (63,80–84).

It takes a much stronger static magnetic field than it takes for an alternating magnetic field to have any effect on biological systems. The physical basis of the weakness of this interaction is the very low magnetic susceptibility of human tissues. Alternating magnetic fields induce currents in tissue by virtue of the changing applied magnetic field. But for static magnetic fields, significant current is only induced when there is motion within the field, either of the body moving or of molecules moving, for example circulating blood (83,85). Other mechanisms of biological action of static magnetic fields have been demonstrated in animals and laboratory systems but have not been shown to be important in humans. These mechanisms include magnetic moment effects on specialized molecules known as magnetosomes. The action of the earth's static magnetic field on magnetosomes in bees, birds, and other animals is important to their navigational processes. Static magnetic fields have also been shown to affect radical pair reactions at modest field levels (14). Because of the lack of influence of static fields on living tissue except at very high magnetic field strength and the relatively uncommon exposure to high-intensity static fields, there has been less research on the health effects of static magnetic fields than on ELF fields. One of the biological effects of exposure to strong static magnetic fields (e.g., >1T) that has been well described is the development of flow potentials in the arterial flow around the heart. These circulatory effects have been studied and explained on the basis of the biophysical interaction of the magnetic field with the moving blood cells and have been described both in animals and humans (82,86–88). The primary manifestation of the circulatory effect is a slight perturbation of the electrocardiogram with no evident clinical effect, at least for fields up to 4T.

Saunders (82) notes in a recent review that acute responses during exposure to static fields above 4T include not only the induction of flow potentials around the heart but the development of aversive behaviors in animals that were allowed to move within the field. There have been a few studies of workers exposed to static magnetic fields, with varying results. A nationwide survey of the reproductive experience of women in the United States who worked at MRI facilities as compared to employees at other jobs showed no evidence among the MRI workers of excess spontaneous abortions, infertility, premature delivery, or low birth weight (89). Milham (90) reported an excess of leukemia mortality among workers in the aluminum industry, but other studies have not found significant disease excesses (91,92). In a recent review, Feychting (81) noted that the limited number of studies of static magnetic fields, along with methodological limitations including difficulties in exposure assessment, made it impossible to draw any conclusions about the potential long-term health effects of static magnetic field exposure.

The relatively recent advent in the last few decades of MRI as a common diagnostic tool has increased greatly the numbers of both patients and medical staff that are now exposed to strong static magnetic fields. MRI scanners also emit RF fields and pulsed gradient magnetic fields with frequency components in the ELF, very low frequency RF, and low frequency RF bands. The history of the utilization of MRI and the studies that have been done have shown this modality to be highly safe and generally without adverse effect (93,94). Some temporary effects have been noted by patients and workers in the strong magnetic fields of MRI machines. These effects in humans include dizziness, a metallic taste in the mouth, and magnetophosphenes, which are visual sensations related to eye movement in a darkened room that have often been described as flashes of light (85,93, 95–97). While these effects of static magnetic field exposure have not been found to be adverse to the health of the individuals, some researchers have raised caution about the potential for the effects being more significant at even higher static magnetic field strengths that might be used in MRI procedures in the future (87,98,99). The development of interventional procedures using MRI with potentially even stronger magnetic fields has led to a few studies of neurobehavioral tests. One recent study showed that processing visual and auditory information in the brain and hand-eye coordination in human subjects were affected by exposure to strong static magnetic fields (99). The authors pointed out that the study was not sufficient to indicate that surgical performance would be affected by the small changes noted in this study but cautioned that additional study is needed.

While the effects of the magnetic fields on tissue are of great interest, that there are important safety concerns, even situations that can be life-threatening resulting from ferromagnetic objects within people (medical implants, shrapnel, etc.) or in the vicinity (tools, cleaning equipment) of the strong magnets built into MRI systems (85,93,100,101).

RADIOFREQUENCY RADIATION

The RF range of the electromagnetic spectrum, 3 kHz to 300 GHz, includes many bands that have specific definitions in the engineering profession (102). Some of the more familiar of these bands include the broadcast television bands of VHF (very high frequency) and UHF (ultra high frequency). The frequencies known as microwaves, from 300 MHz to 300 GHz, are also part of the RF range. In the occupational arena, RF-emitting equipment is found in many industries with such diverse uses as drying, gluing, plastic processing, and sterilization; radio, television, and telecommunications; inventory control, remote control of devices, and radar; and medical uses, such as diathermy and MRI. In the consumer market, wireless telecommunications devices, such as cellular telephones (also known internationally as mobile phones) and wireless computer links to the Internet now have made RF exposure a nearly ubiquitous part of our environment. As little as 15 years ago, the largest consumer use of RF energy was the microwave oven, and health concerns about RF exposure were largely related to smaller, narrowly defined worker populations in certain industrial jobs and the military. The explosion in wireless devices in the last decade has made RF exposure a meaningful topic for the vast majority of the population of industrialized nations, with the current number of cell phone subscribers over 200 million in the United States and over 2 billion worldwide (103). Ambient exposure levels from radio and TV transmission are very low except in certain cases for those who live or work in the immediate vicinity of such broadcast antennas. In the 1970s, an extensive survey was conducted in 15 U.S. cities to determine RF exposures in the environment, primarily from radio and TV broadcast systems (104). The findings from that survey indicated that 99% of persons in the cities surveyed receive RF exposures of less than 0.1 μW per cm^2, which is at least two orders of magnitude below the limit for the general population set forth in the Federal Communications Commission regulations (105,106). Summaries of RF dosimetry and physical and biologic interactions are given elsewhere (107–114).

Research on the biological effects of RF radiation increased greatly after World War II and the introduction of radar (115). This level of research was sustained through the 1980s but dropped off in the 1990s as interest in the health effects of electromagnetic fields shifted to ELF magnetic fields. As the number of users of cellular telephones began to increase rapidly in the mid 1990s and the issue of widespread exposure of the population to RF radiation drew attention in the public media, research activity into the health effects of RF radiation increased in many parts of the world, particularly with respect to the potential for long-term effects of chronic exposure. In contrast to the situation for ELF electric and magnetic fields, the body is a good absorber of RF energy, due to the biophysical properties of water at these frequencies. The primary mechanism for biological effect of RF radiation is the generation of heat in the tissue, when sufficient energy has been deposited. Much of the research in earlier decades was designed to determine thresholds for these responses to acute RF exposures, generally those that would be expected in industrial or military occupations. The question of whether there are any other "nonthermal" mechanisms for biological effects from lower-level RF exposure is the focus of more recent research and a source of controversy.

The unit of measure of the deposition of RF energy into tissue is called the specific absorption rate (SAR). The SAR is defined as the rate of energy absorbed in an incremental mass and is expressed in watts per kilogram (W/kg). The SAR is not possible to measure in practice, but is estimated in phantom models or by numerical modeling calculations. Guidelines for recommended limits for exposure to RF radiation are based on the SAR as the unit of basic restriction. In addition, the regulations for permissible output of RF-emitting devices for personal use (e.g., cell phones) are defined in terms of the allowable SAR that such a device can create in the body. The SAR in a given situation or for a particular device is not predictable based on general characteristics but is a complex function of carrier frequency, modulation, electric-field and magnetic-field strengths, the geometry of the body, the type of tissue in which the energy is absorbed (muscle, bone, fat), and the proximity of the body to the source (near or far field zone of the emitting antenna). In addition, the energy absorption may be highly nonuniform, depending on the frequency of the radiation, the geometry involved, tissue characteristics (layers of tissue that having different water content and dielectric properties, reflective tissue surfaces, body cavities), and other factors. This complexity has meant that the exposure levels in many biologic studies have been inadequately defined, and the studies are therefore difficult to interpret or compare. These dosimetry complexities also complicate in vitro studies where one would expect dose to be easier to control.

Since the American National Standards Institute (ANSI) standard of 1982, a number of different standards setting organizations in North America and Europe have recommended an upper limit of whole-body averaged SAR of 0.4 W/kg over 0.1 hour for occupational exposure (116). This represents about 40% of the resting metabolic rate of an adult human. For the general population, a level five times lower, that is 0.08 W/kg, has been recommended by the Institute of Electrical and Electronics Engineers (IEEE) and ANSI since 1991, though this level and the time of averaging have not been as widely endorsed as the 0.4 W/kg level by all standards setting organizations (117–121).

One of the differences between ELF and RF energy absorption is its penetration into the body. The penetration characteristics of RF energy are part of a continuum, ranging from the superficial penetration of frequencies near infrared to the total penetration of ELF magnetic fields. For RF energy, the penetration is dependent primarily on the frequency of the radiation, though other factors influence it, including the geometry of the body. At the upper limit of the RF range (near infrared), there is very little penetration (122,123). At frequencies used for cell phone transmissions and microwave ovens, about 1 to 2 GHz, the penetration depth is on the order of a few centimeters. At yet lower frequencies, RF energy penetrates into the deepest parts of the body, although the rate of energy deposition in a given layer of tissue diminishes as the penetration increases. While in most situations the greatest heating from an RF exposure will be near the surface, it is possible for there to be internal "hotspots" where the energy deposition is greater in a specific location deeper in the body than it is near the surface (109). It is also possible to feel the warmth of the deposited RF energy, although that also depends upon the frequency of the incident radiation. Even at higher RF frequencies, the deeper deposition of the energy results in a less well-defined heating stimulus for the amount of energy absorbed, as compared to infrared (124). At lower RF frequencies, the energy is largely deposited beneath the most sensitive receptors for thermal sensation such that the feeling of warmth, even in the presence of strong fields, may be weak or even overlooked. Nevertheless, a sensation of warmth can be a valid indication of overexposure to RF radiation in a setting where strong exposures are possible.

The literature on the biologic effects of RF radiation is vast, containing thousands of reports. While it is well established that deposition of RF energy sufficient to raise the temperature of the biological model can cause adverse biological effects, the question of low-level effects is one of continuing debate. The question of low-level effects is also very important in determining if exposures experienced in today's environment have any health consequences. A recent summary of various review reports on the biological effects of RF radiation included more than 20 different reviews (125). There is general agreement among the various review panels to have evaluated this literature in recent years that effects have been observed at levels below that thought to impart a meaningful thermal load on the body or in vitro preparation. However, these review panels are also in agreement that the evidence for these low-level RF effects is inconsistent, in some cases not reproducible, and, while intriguing, does not provide any indication of a relationship to adversely affecting human health (108,110,111). The approach to studying the question of the role of thermal (or nonthermal) effects with in vitro biological models has been either to use very low incident RF energy (often assuming no thermal effect was possible) or to provide an experimental system in which the temperature of the system being studied was clamped and not allowed to increase by removing any heat generated by the RF as it was absorbed. Some researchers have theorized on the basis of biophysical principles that low-level RF exposures that would be below the published guidelines for human exposure could not alter biological function, but the continuing reports of observations of low-level effects continue to raise questions about the plausibility of such effects (15,118,120,126–129).

The effects of RF radiation on macromolecular or cellular function that have been of greatest interest and study include studies of cell proliferation, changes in ion transport across the cell membrane (including calcium efflux), alterations in ornithine decarboxylase activity, changes in gene expression, the stimulation of the production of heat-shock proteins, and DNA damage or alteration in DNA repair, e.g., the formation of micronuclei. For each of these endpoints, the reports are conflicting, and a clear, robust effect with an identifiable dose-response has not emerged. Most genotoxicity studies have been negative, and RF radiation is not thought to be directly mutagenic (108,111,130).

Reproductive or Teratogenic Effects

Most of the experimental studies of adverse reproductive outcomes or teratogenesis have involved RF exposures that were intense enough to cause heating in animals. These reports indicate that RF exposure can be teratogenic when the dose rate is sufficient to cause significant elevation in body temperature of a pregnant animal (30). In a series of studies on RF teratogenesis, Lary et al. (131) also showed that lowering the RF level below the thermal level was not teratogenic. The data indicate a clear time and temperature profile of exposure, with a threshold of temperature, somewhere above 39°C, that is required for these teratogenic effects (132). In two long-term studies using lower power densities in which the thermal effects would be low, Jensh et al. (133,134) found maternal microwave irradiation of rats had no effect on maternal gestational weight gain, birth weight, litter size, fetal resorption rate, or fetal abnormality rate. However, offspring of irradiated animals did show subtle long-term neurobehavioral and developmental deficits (135). Nelson et al. (136), in a series of studies, demonstrated a synergistic interaction of chemical and RF exposure that was teratogenic at doses below that at which the effects occurred with either agent alone. It is not clear how much these interactions in rats could be generalized to occupational exposures of humans. Overall, the results of these experimental RF studies on teratogenesis are consistent with the effects of other forms of heating on reproductive outcome.

There have only been a few human studies that have examined possible reproductive outcome following RF irradiation, other than those involving VDT use mentioned earlier. A retrospective study of a large number of female physical therapists observed a slightly increased risk of miscarriage with a statistically significant trend of increasing risk with increasing exposure, as assessed by a survey, for those using microwave diathermy (137). The relationship to the RF exposure itself is questionable, but the same study did not show an association with use of shortwave diathermy, which would be more likely than microwave diathermy to penetrate to the fetus (138). Other studies of occupationally exposed physiotherapists came up with conflicting results. Kallen and Moritz (139) studied 2,018 Swedish physiotherapists and found that the incidences of perinatal death, serious malformations, short gestational duration, and low birth weight were below expectation in this group. In a nested case–control study, they found a suggestive association between adverse pregnancy outcomes (dead or malformed infants) and work with shortwave equipment during pregnancy. However, a later study based on an overlapping cohort found no exposure-related gradients in reproductive risks (140). In a study of Israeli physiotherapists, Lerman et al. (141) found a statistically significant relationship between low birth weight and RF exposure, while yet another study found no association between shortwave irradiation among female physiotherapists and birth weight or gender ratio of offspring (142).

Hematopoietic, Immune System, and Neuroendocrine Effects

The effects on the hematopoietic, immune, and neuroendocrine systems provide a good example of a basic principle in the effects of RF radiation. In general, the known effects of exposure to RF fields, even for high intensities, are ones that are nonspecific; they do not provide any unique characteristic or unique RF-related outcome as some agents do. This is evident in the effects on these systems. As with other physiologic effects, the best evidence for our current understanding of these nonspecific effects comes from research with acute exposures of laboratory animals.

In a recent review of the response in these physiologic systems to RF radiation, Black and Heynick (143) noted that neuroendocrine responses have only been consistently observed at RF exposure levels at which the body temperature is elevated at least 1°C. The adrenocortical response is like that of a nonspecific stress response and has been shown to be dependent on central nervous system action through the pituitary gland (144–146). Other hormonal responses also fit the generalized stress response pattern as related to heat generated by the RF exposure (143). In a few studies that have examined endocrine endpoints after long-term exposure of rats to low intensity RF radiation, no changes in the hormone levels were observed (147, 148). Immunologic effects observed after in vivo exposure of laboratory animals also showed an association with an increase in body temperature as well as a similarity to changes caused by the administration of corticosteroids (149–151), raising the possibility that the immune and endocrine responses to RF radiation might be linked, though they have not been measured in the same experiment.

There have been few evaluations of these systems in human studies. A few older reports from Eastern Europe reported alterations in these systems, but they are difficult to interpret because of a lack of exposure information and other methodological limitations, and no recent updates on those occupational groups have been reported (152–154). There was considerable attention given to the potential health effects of deliberate microwave irradiation of the U.S. embassy in Moscow, but a study of that group of workers found no excess of morbidity due to blood diseases in comparison with that in employees at other Eastern European U.S. embassies (155,156). High lymphocyte counts that were found among the Moscow embassy employees did not correlate with microwave exposure.

Nervous System Effects

A number of different biological models and endpoints for the response of the nervous system to RF radiation exposure have been studied extensively, including effects on nerve tissue in vitro, blood-brain barrier (BBB) integrity, and behavioral performance in animals, as well as neurologic and psychiatric effects in humans. The alteration of animal behavior during acute RF exposure has been used as the threshold of adverse effect that forms the basis of the recommended exposure limits for whole-body RF radiation (118–120). In one of the most thorough sequences of studies of this kind, de Lorge et al. (157–159) evaluated operant performance disruption in three different species and identified thresholds of work stoppage that ranged from about 3 W/kg to about 6 W/kg depending upon the frequency of the RF radiation and the species. While not all reports of RF effects on behavior are consistent with these thresholds, many other behavior studies confirm the validity of these results and corroborate these findings in other laboratories, with other exposure paradigms and other behavioral testing schemes. Another important finding in these studies was the strong correlation with body temperature and behavioral disruption, with the threshold for behavioral effects corresponding to a 1°C core body temperature rise (159). Only a few studies have evaluated animal behavior during or after chronic, low-level RF radiation exposure, and these studies have been inconsistent and inconclusive (159). Learning and memory have also been the topic of many animal studies. D'Andrea et al. (160) have reviewed this work and found that RF radiation can alter animal learning if the exposure is intense enough to raise body temperature, but the effects on learning at lower level exposures noted in a few studies have not been found consistently in independent experiments using similar experimental protocols.

The proliferation of cell phones, with the most common RF exposure being to the head of the user, has stimulated much interest in studies of central nervous system function in humans. Many laboratory studies have been added to the literature in the past decade, including studies of electroencephalograms (EEG) during sleep and awake. Some of the studies of brain activity during sleep have shown subtle effects on EEG spectral characteristics (161), but other studies did not report such an effect. Comparison between different studies is difficult due to variations in the experiments; thus the overall picture from the various studies is unclear (162). In the studies of awake subjects, RF exposure generally produced no influence on the EEG (160). There have been only a few studies of the effects of environmental exposures to broadcast radio or TV transmissions or cellular phone base stations on cognitive performance and sleep disturbance. The various expert groups that have reviewed the literature and the potential exposures from such towers and especially the base stations have been in agreement that the low levels of exposure generally created by such towers are not likely to cause any health effects (111,163,164). A recent study of residents living near cellular phone base stations reports a relation of measured power density of exposure to some symptoms, such as headaches and the response rate to specific tests, but could not determine whether the effects were caused by the RF exposure or some other factor (165).

The first reports that RF radiation could alter the (BBB) at low levels of exposure appeared in the 1970s and generated a great deal of interest (166,167). As work on the effects of RF exposure on the BBB proliferated, it became clear that RF exposures that raised core body temperature could alter the permeability of the BBB, but the question of possible effects at low-level RF exposure has remained unclear (108,160). Studies by Salford et al. (168–170) using frequencies at or near cellular phone frequencies have consistently reported BBB changes after low-level exposure, but other researchers have reported no changes for exposures at that level (171,172). In other work on the nervous system, Lai (173) has done an extensive series of work on neurochemical changes (e.g., endogenous opioid systems and cholinergic activity). This study showed activation of the opioid systems in ways consistent with the hypothesis that RF radiation exposure of the rat acts as a nonspecific stressor. The neurochemical effects reported by Lai occurred at exposures at relatively low SAR (<1 W/kg) as well as at higher SAR. The potential health significance of these changes has not been clarified (160).

In the 1960s and 1970s, there were reports from the Soviet Union and a number of Eastern European countries of autonomic and central nervous system disturbances and "radio wave sickness," a complex of symptoms including headache, dizziness, loss of memory and concentration, irritability, sleep disturbance, weakness, decrease in libido, depression, and anxiety (154,174–177). These studies have been difficult to interpret as the exposure assessment was weak, the symptoms are also typical of stress situations, and the studies lacked well-defined control groups for comparison. These symptoms were reported to be reversible after the exposure was discontinued.

Two studies of Swedish workers occupationally exposed to the strong RF sources of plastic sealing machines reported a lower performance in a two-point discrimination test of the fingers, compared to controls (178,179). These observations, though in small numbers of workers, suggest the possibility of peripheral neurological problems in workers whose hands and arms are chronically exposed to strong RF fields. A summary of case reports of RF overexposures also supports the possibility of neurological effects (180).

The issue of EHS mentioned earlier with respect to ELF electric and magnetic fields is also evident in the literature for RF radiation effects and particularly for the use of cellular phones (181,182). Based on the limited studies available, it does not appear that RF radiation is the cause of such health problems, even when they occur during the use of cellular phones (160,181,183).

Cataracts and Other Ocular Effects

A review of the experimental literature concluded that no well-documented studies show lens changes or cataracts to result from RF radiation exposure levels less than about 100 mW per cm^2. The threshold for irreversible changes is about 150 mW per cm^2 for a single 100-minute exposure (184). Most mechanistic studies have concluded that thermal effects are central to cataractogenesis, although there may be photochemical effects as well (185). A recent review of the subject indicated the heat-labile antioxidant enzymes such as glutathione peroxidase are inactivated so that protein sulfhydryl groups are oxidized and high-molecular weight aggregates are formed. These changes alter the orderly structure of the lens's cells, which is crucial for its translucency (186).

The first case of microwave cataractogenesis was reported in 1952 in a 20-year-old radar worker, and in all, more than 50 reported cases presumably have been induced by microwaves (184). Most studies conducted more recently have failed to find any microwave-associated ocular disease. Findings of three medical record-based studies have been negative: a study of 20,000 Naval radar workers, a case–control study of 2,900 Army and Air Force veterans with cataracts and 2,100 without cataracts, and the Moscow U.S. embassy study (155,187,188). An Australian study showed an increased prevalence of posterior subcapsular opacities among a group of 53 radio linemen, but the power densities around their work areas were sometimes very high (up to 3900 mW per cm^2) (189). Ocular examination studies by a number of investigators have shown no increase in lenticular opacities or other ocular damage related to microwave exposure at power densities less than 10 mW per cm^2 (190,191). Cataracts have been observed in rabbits (but not monkeys) when experimental RF exposures were very high; 2450 MHz for more than 30 minutes at power densities causing extremely high dose rates (>150 W per kg) and temperatures ($\geq 41°C$) (192). Long-term studies up to 4 years in monkeys have been negative for ocular effects including cataracts, confirming the lack of ocular effects in human populations exposed for long periods of time to low-level RF energy (192). In summary, the literature is clear that very high RF exposures with very strong heating of the eye can cause cataracts in laboratory animals, but it is doubtful that humans could sustain such intense exposures without sensing strong heating or even pain and moving to reduce the exposure.

Cancer Induction

For many years, little consideration was given to the possibility that RF radiation could cause cancer. The photon energy in the RF spectrum is too low to cause ionization of molecules, and the in vitro evidence indicated that RF radiation was not mutagenic (193,194). A study of a large number of U.S. Navy veterans with likely exposure to RF radiation and another study of Polish radar workers each found no excess rate of cancer in the exposed group (187,195). In their comprehensive review of the topic of the biologic effects of RF radiation, Michaelson and Lin (109) devoted only one paragraph to the question of cancer. Several things happened in the early 1990s that changed the research interest in RF and cancer. Chou et al. (147) published the results of a large, high-quality animal study in which rats (100 exposed, 100 control) had been exposed to RF radiation for nearly their entire life (approximately 2 years). Even though there was no difference in most endpoints, including the lifespan of the two groups, histopathology revealed a small but statistically significant higher number of animals with malignant tumors in the exposed group. At about the same time, anecdotal evidence caused a stir in the mainstream media over a possible association between cellular phone use and brain cancer, and the U.S. Senate held hearings on the question of an association between police radar use and testicular cancer (196). In addition, the number of cellular phone users was increasing almost exponentially during the mid 1990s, which elevated the public health importance of any possible cancer risk of RF radiation exposure.

In the last decade, many studies focused on evaluating the potential health effects of long-term, low-level RF radiation exposure have been conducted. Elder (197) has recently reviewed 18 animal studies, most conducted in the last 10 to 15 years, in which the experiments were conducted over a long enough time to evaluate survival of the RF-exposed and sham-exposed groups. Sixteen of the studies also evaluated cancer outcome in the animals, with some conducting a histopathological review of all major tissues, while others concentrated on tumors in specific tissues, usually the brain. An early study by Szmigielski et al. (198) had suggested a hypothesis that the RF exposure was a cancer promoter rather than a cancer initiator. That hypothesis has gained further support from other laboratory experiments and also spurred the use of some biological models, including transgenic animals prone to cancer, in order to evaluate the cancer promotion hypothesis. One study not included in Elder's review was done with long-term RF exposure of a transgenic mouse strain (Eμ-Pim1) and reported a twofold increase in lymphoma in the mice exposed to 900 MHz-RF over an 18-month period (199). A later attempt to replicate that experiment did not find an increase in lymphoma (200). The other long-term animal studies conducted in the past decade have nearly all been negative, in that no association was shown with RF exposure and cancer development. One weakness of these studies is that nearly all of them used a single dose of RF exposure, limiting the conclusions that can be drawn. Collectively, the animal studies are largely negative for cancer development (108,197).

Human studies of long-term, low-level RF exposure have also been conducted by many researchers in the past 10 to 15 years. These studies have primarily been directed at cellular phone users, most commonly in case–control studies focusing on brain cancer or other tumors of the head and neck. Several reviews have been published on the epidemiological literature (111,201–204). These reviews have indicated that the studies have generally not found an association between RF exposure (e.g., cell phone use) and cancer development. However, a number of individual studies are limited in having too few cases to have a high power of detecting a small increase in risk of cancer. One of the notable exceptions to the trend of negative studies is a series of investigations by Hardell et al. (205,206) of Swedish mobile phone users. The most notable characteristics of their results were that they saw an increase in both malignant and benign tumors, with the greatest risk being for analog phones (compared to digital phones) for tumors ipsolateral to the side of the head on which the phone was used and for phone use greater than ten years. In another study (see the description of the INTERPHONE study in the paragraph that follows), the authors of a combined report from five Northern European countries on the association of acoustic neuroma with mobile phone use reported that their findings "do not support an increased risk of acoustic neuroma in the first decade after starting mobile phone use" (207). With respect to their finding an increased risk for mobile phone use greater than 10 years, they concluded that "On balance, the evidence suggests that there is no substantial risk of acoustic neuroma in the first decade of use, but the possibility of some effect after longer periods remains open."

In 2000, after conducting a feasibility study, the IARC began a multinational study of mobile phone users known as the INTERPHONE study (208). Thirteen nations have been participating in these series of case–control studies. The objective of these studies is to assess whether RF exposure from mobile phones is associated with tumors of the head and neck. The primary source of information is an in-person computer-assisted interview with the subjects. Individual study teams began publishing their results in the last year, and the main, pooled analysis of all the data should be available in the next year. There is much anticipation that the results of the combined INTERPHONE studies will provide some clarity to the uncertainty surrounding the existing literature on long-term effects of low-level RF exposure. The possibility exists, however, that questions about long-latency, particularly that requiring more than 10 years of exposure (such as reported by Hardell et al.) will not be answered by the INTERPHONE study simply because there were too few mobile (cellular) phone users in the study population with that long a period of use.

Medical Evaluation of Overexposure to Radiofrequency Radiation

While the debate continues over whether there are any adverse health effects from long-term low-level exposure to RF radiation, the fact remains that there continue to be acute overexposures to RF radiation in the workplace, for which an overexposure is defined as an exposure at a level above that recommended by the IEEE or ICNIRP exposure standards. Such overexposures, though uncommon, occur most often on or around RF-emitting antennas, such as the broadcast towers associated with radio and TV transmissions. One of the complicating aspects of such tower environments is that many towers or antenna platforms are now colocated on a single tower or at a single location on multiple towers. An overexposure to RF can cause injury that needs medical attention or at least create an incident that needs medical evaluation. Some case reports are available in the literature, though there are not a lot of them. In one case, a painter working on a radio antenna on top of a large skyscraper suffered serious leg burns (from induced current) when the antenna was inadvertently energized while he was on it (209). In another review of exposure to high RF radiation levels during work on transmission antennas, six men exhibited symptoms and signs that included headache, paraesthesia, diarrhea, malaise, and lassitude (210). Reeves (211) reviewed 34 cases of potential overexposure to RF in the U.S. Air Force and reported that neurological findings were minimal and that there were no opthalmologic consequences of the exposures. The patients did report sensing warmth during the exposure that was positively associated with the power density of exposure. A few patients reported burning pain that resolved over several weeks.

As noted earlier, there are no specific RF-induced ailments to be evaluated in overexposure cases, except for heating. The IEEE Committee on Man and Radiation (COMAR) has published a basic discussion of an approach to medical evaluation of a potentially overexposed individual (212). Ocular examination is recommended, particularly for shorter RF wavelengths, such as those that occur in the vicinity of 1 GHz and higher frequencies. Physicians should also be attentive to patient reports of heating or other sensations, which may provide clues to how strong the exposure may have been. Finally, consideration may need to be given to electromagnetic interference with implanted medical devices. While the warning signs related to microwave ovens and pacemakers are obsolete, today's complex electromagnetic environment, including antitheft portal devices in stores, digital wireless communications devices, and strong EMF sources in industry, does present the potential to cause interference with medical implants under certain conditions (213–219).

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EDITED BY

WILLIAM N. ROM, MD, MPH

Sol and Judith Bergstein Professor of Medicine
Director
Division of Pulmonary and Critical Care Medicine
Departments of Medicine and of Environmental Medicine
New York University School of Medicine
New York, New York

ASSOCIATE EDITOR

STEVEN B. MARKOWITZ, MD

Professor and Director
Center for the Biology of Natural Systems
Queens College, City University of New York
Adjunct Professor
Department of Community and Preventive Medicine
Mount Sinai School of Medicine
New York, New York

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