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AIMS & SCOPE

Biomedical engineering has been characterized as the application of concepts drawn from engineering, computing, communications, mathematics, and the physical sciences to scientific and applied problems in the field of medicine and biology. Concepts and methodologies in biomedical engineering extend throughout the medical and biological sciences. This journal attempts to critically review a wide range of research and applied activities in the field. More often than not, topics chosen for inclusion are concerned with research and practice issues of current interest. Experts writing each review bring together current knowledge and historical information that has led to the current state-of-the-art.

Each issue contains one or more critical reviews of specified topics representing applied, clinical and basic science areas. Most articles contain in-depth appraisals of the current state-of-the-art in a specific area of research or practice and provide complete and up-to-date bibliographies. Each review attempts to be nearly exhaustive in a constrained area rather than broad and overarching. The critical evaluations of current research and development issues include interpretive discussions of major problems. From time to time, a series of articles in a related topic area are published in order to give comprehensive coverage. Collaborative works generated by multiple authors are frequently used to provide in-depth coverage from multiple viewpoints. Each article is reviewed by one or more independent experts in the field.

The editor invites comments and suggestions about the contents of the reviews.

John Bourne
Editor

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Health Risks of Electromagnetic Fields. Part I: Evaluation and Assessment of Electric and Magnetic Fields

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ABSTRACT: Exposure to electric and magnetic fields (EMF) emanating from the generation, distribution, and utilization of electricity is widespread. The major debate in recent years has focused on the possibility that exposure to EMF may result in adverse health consequences, including the development of cancer. This article provides a review and evaluation of potential health risks associated with residential and occupational exposure to EMF. In addition to reviewing data from laboratory, epidemiology, and clinical studies, we examine exposure data from field measurement surveys and exposure guidelines that have been established for EMF. Currently, the evidence in support of an association between EMF and childhood cancer is limited, although this issue warrants further investigation. Evidence of an association between EMF exposure and adult cancers, derived largely from occupational settings, is inconsistent, precluding clear conclusions. There is little evidence of an association between EMF and noncancer health effects. Epidemiological studies of EMF and population health are limited by exposure measurement error and the lack of a clear dose/response relationship in studies suggesting possible health risks. Further research is needed to clarify the ambiguous findings from present studies and to determine if EMF exposure poses a health risk.

KEY WORDS: standard development, measurement survey, epidemiology, cellular and animal studies, clinical studies

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I. INTRODUCTION

The use of electricity results in the production of electric and magnetic fields (EMF). There are two types of EMF, classified according to the frequency range: extremely low-frequency (ELF) fields and very low-frequency (VLF) fields. ELF fields are defined as those having frequencies up to 3 kHz. VLF fields cover the frequency range of 3–30 kHz. Because of the quasistatic nature of the electromagnetic (EM) fields at these frequencies, electric and magnetic fields act independently of one another and are measured separately. Electric fields created by voltage and measured in volts per meter (V/m), are present whenever an electric appliance is plugged in. The appliance need not be turned on for electric fields to be detected. Magnetic fields, induced by alternating current (AC) and measured using the derived quantity magnetic flux density (B) in Tesla (T) or Gauss (G), are present when the appliance is turned on. The strength of EMFs decrease as we move away from their sources. EMF exposure is commonly found in and around our homes and offices [Habash, 2001].

Electric and magnetic fields can occur separately or together, and accordingly it is possible for humans to be exposed to just one of these fields or both of them. For example, when a power cord is plugged into a socket outlet, it creates an electric field along the cord. When the lamp is turned on, the flow of current through the cord creates a magnetic field, and the greater the current, the stronger the magnetic field. In the meantime, the electric field is still present. In addition, it is possible for humans to be exposed to various levels of EMF. Power transmission lines, for example, generate strong electric and magnetic fields. However, distribution lines generate weak electric fields but can generate strong magnetic fields, depending on the number and type of loads they supply.

Although electric and magnetic fields often occur together, most of the concern has focused on the potential health effects of magnetic fields. The basis for this concern is that magnetic fields are difficult to shield and easily penetrate buildings and people, as opposed to electric fields, which have very little ability to penetrate buildings or even human skin. Because the use of electricity is ubiquitous and plays a vital role in society's economy, the possibility of harm from EMFs to electric utility customers and workers deserves attention.

Whether or not there are health consequences associated with the EMF emanating from the generation, distribution, and use of electricity is a controversial issue, one in which the tension between risks versus indispensable advantage comes into play. This is a common debate when complex environmental issues with considerable health and economic outcomes are scientifically analyzed. There are also economic consequences—for example, electrical utilities sometimes have had to redirect high-voltage power lines around populated areas or even stop their construction. The real estate industry is also increasingly concerned with issues related to EMF exposure. These include equipment interference, potential liability, property valuation, premises abandonment, and tenant concerns about potential health effects. Concerns about hazard have often pushed manufacturers to improve products by providing better shielding, which has a positive impact on the EM compatibility and performance of the product itself. The cost–benefit ratio for making such improvements is always a concern, but at the same time it is useful to note that engendering public trust is very important too.

This article provides a review of potential health risks associated with exposure to EMF. Our review considers exposure guidelines, dosimetry, and field measurement surveys as well as currently available evidence from laboratory, epidemiological, and clinical studies on possible health impacts. We conclude with an overall assessment of the current state of the science on the health risks of EMF exposure.

II. EMF EXPOSURE GUIDELINES

Several decades of research in the area of bioelectromagnetics has led to a scientific consensus on the safety of EM fields. Expert committees reflect this consensus when developing exposure guidelines. For the purpose of this article, "safety standard" is one that specifies measurable field values that limit human exposure to levels below those deemed hazardous to human health [Erdreich and Klauenberg, 2001]. These standards consist of regulations, recommendations, and guidelines that would not endanger human health. The development of safety standards presupposes certain procedures, including (1) systematic review of the scientific literature, (2) identification of health hazards and risk assessment, and (3) selection of maximum permissible exposure (MPE) values that produce an environment free from hazard.

Hazard can be an object or a set of circumstances that could potentially harm a person's health. Risk is the likelihood, or probability, that a person will be harmed by a particular hazard [WHO, 2002]. The more clearly the hazard is understood, the sooner a safety procedure is established. At the end, safety is a social choice made by people, governments, and organizations. It assumes that the cost–benefit ratio is favorable and that options exist for minimizing exposure.

In relation to EM human health effects, most scientific information obtained from cellular and animal studies provides the foundation for assessing potential risks to humans. Studies in humans provide direct information regarding health effects and help validate animal studies. Epidemiological studies are more likely to provide information regarding the nature of the effect rather than to provide detailed exposure–response or dose–response information. When extrapolating data from animals to develop exposure limits for humans, adjustments are usually needed to account for several potential limitations in the process [Dourson and Stara, 1983].

The results from these studies permit the identification of MPE values indicating that below a certain threshold, an EM field level is safe according to the available scientific knowledge. The permissible level is not an exact line between safety and hazard. However, no adverse effects have been shown to exist below this defined limit, and possible health risks increase with higher exposure levels. Often, the MPE level is coupled with a "safety or uncertainty factor." This implies that a safety limit in a standard is set just below the injury threshold (many times even lower) for a sensitive individual. The incorporation of a suitable safety factor provides a protection for both occupational and residential environments. This is because people in occupational settings can carry out risk analysis and risk management more accurately, whereas public environment is less controlled, and usually individual members of the public are unaware of their exposure. Moreover, the public may be regularly exposed and may not be expected to take adequate precautions to reduce or avoid the exposure.

Many institutions and organizations throughout the world have recommended safety limits for EMF exposure. These include the Institute of Electrical and Electronic Engineers (IEEE) [IEEE, 1992, 1999], the National Radiological Protection Board (NRPB) of the UK [NRPB, 1993], the International Commission on Non–Ionizing Radiation Protection (ICNIRP) [ICNIRP, 1998a,b; ICNIRP, 2003], the Swedish Radiation Protection Institute [TCO, 1999], Health Canada [Safety Code 6, 1999], and the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) [ARPANSA, 2002]. Table 1 shows various MPE values for EMF exposure [Habash, 2003a,b].

Most of the exposure guidelines use a two–tier standard, indicating a basic restriction in terms of current density (J) and corresponding investigation levels or reference levels in terms of external field strengths (E). The exposure limits range from

TABLE 1. Maximum Permissible Exposure (MPE) Values for EMF

Year: Standard	Magnetic field safety level	
1992: ANSI/IEEE	205 μT	
1993: NRPB	50 Hz: 1600 μT 60 Hz: 1330 μT	
1998: ICNIRP	General public: 83.3 μT	Occupational: 420 μT
1999: The Swedish Standard	Video display terminals ELF (5 Hz-2 kHz): ≤ 0.2 μT VLF (2 kHz-400 kHz): ≤ 0.025 μT	
1999: Safety Code 6	General public: 2.75 μT	Occupational: 6.15 μT
2002: ARPANSA	General public: 3 kHz–100 kHz: 6.1 μT	Occupational: 3 kHz–100 kHz: 31.4 μT

0.1 μT = 1 mG

a few microteslas (μT) up to 1300 μT. The levels for those occupationally involved in various electrical industries are set higher than are those for the general public.

II.A. Institute of Electrical and Electronics Engineers (IEEE)

The first formal standards project was initiated in 1960 when the American Standards Association (now the American National Standards Institute, ANSI) approved the Radiation Hazards Standards Project. This project, under cosponsorship of the Department of the Navy and the Institute of Radio Engineers (now the IEEE) included the establishment of Committee C95, which published its first standard in 1966 [ASA, 1966]; revisions of the standard were published in 1974 [ANSI, 1974] and 1982 [ANSI, 1982]. In 1988, the C95 committee continued its work as Standards Coordinating Committee 28 (SCC28) under the sponsorship of the IEEE Standards Board (now the IEEE Standards Association Standards Board, SASB) and established the ANSI/IEEE C95.1-1991 standard [IEEE, 1992, 1999; Osepchuk and Petersen, 2003].

The ANSI/IEEE C95.1-1991 standard recommends that exposure averaged over any 6-minute period and over a cross-section of the human body should not exceed 0.614 kV/m for the electric field and 163 A/m (205 μT) for the magnetic field. The ANSI/IEEE standard is designed to keep the induced current in the human body at least a factor of ten below the lowest reported stimulation thresholds for electrically excitable cells.

The IEEE at present does not have a detailed standard covering the lower frequencies relevant to the electric utility power system. However, a new standard is being prepared by the International Committee on Electromagnetic Safety (ICES) of the IEEE, which will be based on known interactions of internal electric fields with the different parts of the nervous system [Renew and Glover, 2002]. In general, the goal of the ICES is to have oversight not only of the activities of SCC28 but of the product safety committee SCC34, as well as any new committees that would be established, to develop environmental standards [Osepchuk and Petersen, 2003]. The types of documents produced by the ICES are standards, recommended practices, and guides. A recent document by the ICES (IEEE C95.6-2002) [IEEE, 2002], which covers human exposure to EMF (0–3 kHz), will be of interest to many international entities.

II.B. National Radiological Protection Board (NRPB)

The NRPB provides information and advice to officials in the United Kingdom with responsibility for protection from radiation hazards either in the population as a whole or within population subgroups. The recommended NRPB guidelines [NRPB, 1993] are the same for occupational and public environments. The basic restriction specified by the NRPB is an induced current density of 10 mA/m^2 in the head and trunk, while the investigation levels for EMF exposure at 50 Hz are 12 kV/m and 1600 μT, respectively [Renew and Glover, 2002].

II.C. International Commission on Non-Ionizing Radiation Protection

The ICNIRP's mission is to coordinate knowledge of protection against various nonionizing exposures in order to develop internationally accepted recommendations. The ICNIRP guidelines [ICNIRP, 1998a,b; ICNIRP, 2003] specify "basic restrictions" and "reference levels." Basic restrictions on exposure to magnetic fields are based on established adverse health effects. For magnetic fields below 100 kHz, the physical quantity used to specify the basic restrictions is current density induced inside the body. Reference levels are values that are provided for practical exposure assessment purposes to determine whether the basic restrictions are likely to be exceeded. Compliance with the reference levels is designed to ensure compliance with the relevant basic restriction [ICNIRP, 2003].

In 1999, the Council of the European Communities issued recommendations concerning exposure of the general public to EM fields, adopting the ICNIRP guidelines [CEC, 1999]. The restrictions are based on the ICNIRP guidelines for the general public (with a basic restriction of 2 mA/m^2). However, many European states have introduced lower precautionary-based exposure limits, such as Italy (2 μT) in 1998 and Switzerland (1 μT) in 1999. The above exposure limits are significantly below those designed to protect against acute effects.

II.D. Swedish Standards

Sweden has been a leader in developing recommended visual ergonomic and EM emission standards for computer displays. Two prominent measurement and emission guidelines for monitors have emerged during the past few years. One, known as MPR II, prescribes limits on EMF emissions in the ELF and VLF ranges, as well as electrostatic fields. Many major manufacturers of computer displays have embraced the Swedish guidelines. Nevertheless, the Swedish Confederation of Professional Employees, or TCO, which represents over a million workers, requested more restrictive limits and test protocols. TCO published its own series of guidelines—TCO'90, TCO'92, TCO'95, and TCO'99—which in reality are a copy of MPR-II with some adjustment [TCO, 1999]. In addition, recent TCO guidelines include those for energy consumption, screen flicker, luminance, and keyboard use.

II.E. Restrictions

Most of the above exposure guidelines are based on recognized and reproducible interactions between EMF and the human body. The observed effects were all acute effects of EMF exposure on excitable tissue, such as nerve and muscle. The basic restriction in all exposure guidelines has to date been specified in terms of induced current density as the principle measure of interaction of EMF with the body rather than the more directly relevant internal electric field. The use of current density originated for the pragmatic reason that data were more readily available on current density than on electric field. The data used in the early days to determine the thresholds for nerve and muscles tended to be investigated using injected currents, with the current density being calculated from the injected current on the basis of the geometry without requiring conductivity information [Renew and Glover, 2002]. Other investigators suggested the use of internal electric field as a basic restriction in future EMF exposure guidelines [Bailey, 2002; Stuchly and Dawson, 2002; Reilly, 2002].

III. MEASUREMENT SURVEYS AND DOSIMETRY

Engineering contributions in the field of EM risk have made it possible to assess the field strength or power density from exposure from an EM source and check its compliance with exposure guidelines. Theoretical calculations are adequate in some situations, but measurements often prove more conclusive and less expensive, particularly at multiple-source sites. Therefore, theoretical calculations, particularly computational methods, are often not enough to assess compliance with safety limits. For this reason, EM measurements are usually performed to assure compliance with relevant guidelines in order to prevent overexposure conditions that could pose short- and long-term health problems. Measurements also are needed when the calculated fields are close to the threshold for overexposure or when fields are likely to be distorted by reflection from various objects.

In addition, assessment of EMF exposure levels for the general public and associated with particular occupations provides required background information for epidemiological assessment of disease risk. Major difficulties with respect to exposure assessment include the lack of knowledge about a relevant metric and the relevant induction period, the incomplete characterization of exposure sources, and the inability to combine exposures from different sources into one metric [Ahlbom, 2001].

III.A. Sources of EMF Exposure

EMF in the environment comes from a number of sources. The level of these fields, particularly magnetic fields, are called *background level.* The background level of schools, hospitals, homes, and workplaces is always increasing because of the rapid increase in the use of electricity. The background field must be considered while measuring the magnetic field from a particular source.

Any residential or occupational site is subject to coincident exposure from many EMF sources external and internal to the site itself. External sources include high-voltage power lines, distribution lines, underground cables, substations, transformers, and transportation systems. In the workplace, sources of EMF include computers, fax machines, copy machines, fluorescent lights, printers, scanners, telephone switching systems, motors, induction heaters, electronic article surveillance (EAS), demagnetizers, security systems, and metal detectors. In homes, there are two immediate sources of EMF. The first type includes internal wiring, meters, service panels, subpanels, and grounding systems. The second type includes electrical appliances such as electric blankets, electric waterbed heaters, hairdryers, electric shavers, television (TV) sets, video display terminals (VDTs), stereo systems, air conditioners, fluorescent lights, refrigerators, blenders, portable heaters, washers and dryers, coffee makers, vacuum cleaners, toasters, and other household appliances.

EMF exposures within residences vary from over 150 μT and 200 V/m a few cm from certain appliances to less than 0.02 μT and 2 V/m in the center of many rooms. Appliances that have the highest magnetic fields are those with high currents or high-speed electric motors (e.g., vacuum cleaners, microwave ovens, electric washing machines, dishwashers, blenders, can openers, electric shavers) [Preece et al., 1997]. Background magnetic fields are in general between 0.1–0.3 μT.

Underneath overhead power lines the average magnetic flux density can be up to 30 μT for multiconductor 765 kV lines and 10 μT for 380 kV lines. Around power plants, average fields may be as high as 40 μT. Certain occupational environments may encounter magnetic fields up to 130 milliteslas (mT). Actual magnetic fields depend on distance, voltage, current, and wire arrangement. However, actual electric fields are affected only by distance, voltage, and wire arrangement.

Exposures from arc welders and electrical cable splicers may exceed 100 μT and 5000 V/m. Exposure to power-frequency EMF is poorly correlated in occupational settings. Electric trains can also be a major source of exposure, as magnetic fields at seat height in passenger cars can be as high as 60 μT [Chadwick et al., 1998].

Safety regulations stipulate field limits in occupational and public environments, and thus there becomes a need for field measurement surveys. Such surveys are usually performed for one or more of the following reasons: (1) to evaluate a space where electrical devices are being greatly affected by electrical installation systems or other electromagnetic interference (EMI) sources; (2) to evaluate the impact of power lines or other electrical facilities and provide guidance in the installation of further structures; (3) to assess the exposure conditions in homes or offices in order to assure compliance with relevant safety standards; and (4) to prevent overexposure conditions that may pose short- and long-term health problems.

III.B. Site Surveys

A complete survey of any site requires measurements of personal exposure and background fields. Before any assessment of emissions from the EMF source is possible, it is important to define the background field. This is accomplished by turning off the source under measurement and taking readings from the surrounding area. If the background field is relatively high (>0.5 μT), the contribution of the assigned appliance to the environment may be undetectable.

The instruments used to measure EMF are well developed, especially those designed to measure magnetic fields. Besides simple handheld survey meters, there are now portable personal meters that are able to record and illustrate the various characteristics of field exposure. There are three common types of field survey: spot, contour, and dosimetric. A spot survey, suitable for residential and small commercial sites, collects data in spots such as the center of an area or other selected points and arranges these data in a table format, referenced to a layout of the surveyed area. A contour survey is suitable for most commercial applications and assessment of outdoor areas, especially near power lines. In that sense, the mapping wheel is a suitable tool to conduct this survey. A dosimetric survey collects field data at a fixed point in an area (residential or workplace) in timed increments over a defined period (hours or days). It is useful to monitor the variation of fields and record the peaks in certain areas over various periods of time.

An important step in the process of measurement is to classify the area under investigation either as *occupational* or *public.* Such a distinction is necessary before measurements are carried out to ensure that proper exposure levels are used for evaluation and comparison. Various measurement surveys have been conducted in North America [Zaffanella et al., 1993; Zaffanella and Kalton, 1998; Deadman et al., 1999; Kaune et al., 2000; Kelsh et al., 2003] and Europe [Juutilainen et al., 1989; Preece et al., 1996; Vistnes et al., 1997; Clinard et al., 1999; Brix et al., 2001; Tardón et al., 2002; Forssén et al., 2002; Ptitsyna et al., 2003] (Table 2). In North America, power systems operate at a frequency of 60 Hz. However, utilities in Europe, Asia, and other places in the world supply users with 50 Hz of electrical power. This means

TABLE 2. Summary of EMF Measurement Surveys

Author	Country	Type of study	Results
Zaffanella, 1993	USA	Residential, spot (900 homes)	Median field: 0.06 μT (28% > 0.1 μT; 11% > 0.2 μT; 2% > 0.5 μT)
Zaffanella & Kalton, 1998	USA	24-hour personal	Average field: 0.09 μT (44% > 0.1 μT; 14% > 0.2 μT; 2.5% > 0.5 μT, <1% > 0.75 μT
Kaune et al., 2000	USA	Occurrence of magnetic field events with 2–200 kHz (156 homes)	Homes located in rural surroundings had less transient events (3.3 nT and 33 nT) than homes in suburban/urban areas.
Kelsh et al., 2003	USA (California and New York)	Personal and survey Garment workers (3 sites)	Mean personal measurements at waist for sewing, range 0.18–3.1 μT, and survey measurements, range 0.10–2.7 μT
Deadman et al., 1999	Canada (5 provinces)	24-h average exposure of children	Geometric mean (GM): 0.085 mT (15% > 0.2 mT). GM: 12.3 V/m. Quebec had the highest levels of fields; Alberta had the lowest. Electric heating, air conditioning, and housing type appeared to be useful predictors of magnetic field exposures.
Juutilainen et al., 1989	Finland (Kupio)	Residential (37 homes)	24-hour GM: 60 nT
Preece et al., 1996	UK (Avon)	Spot and personal, (50 homes)	Mean: 0.011–0.023 μT; overall mean (0.017 ± 0.003) μT with power on Mean: 0.008–0.015 μT: overall mean (0.012 ± 0.002) μT with power off
Vistnes et al., 1997	Norway (Oslo)	Personal (65 school children living 28–325 m from 300 kV line)	24-hour GM: 15 nT
Clinard et al., 1999	France (French dwellings)	Residential	GM < 0.010 μT, indoor/outdoor measurements (only 5% > 0.12 μT)

Author	Country	Type of study	Results
Brix et al., 2001	Germany (Bavaria)	Personal (1952 people)	For 50 Hz: mean = 0.101 μT; individual medians = 0.047 μT. For people living next to railway lines (16 2/3 Hz): mean = 0.156 μT; Median = 0.102 μT
Tardón et al., 2002	Spain (Oviedo; Barcelona)	Environmental (50 schools)	Median: 0.015 μT in Oviedo, 0.016 μT in Barcelona. Avg. exposure higher in Barcelona (mean 0.057 μT) than in Oviedo (mean 0.017 μT). In playgrounds, median level 0.0095 μT and maximum 0.46 μT.
Forssen et al., 2002	Sweden (Stockholm)	Personal (97 adults and children)	For adults living close to power lines, level of exposure at work was exceeded by residential exposure. For subjects living >100 m from line, situation was the opposite. Even if subjects were highly exposed (≥0.2 μT) at work/school, they spent 71% of total time in fields. < 0.1 μT if the level of exposure at home was low (0.1 μT).
Ptitsyna et al., 2003	Russia and Switzerland	Occupational (Russian DC and Swiss AC powered 16.67-Hz electric trains)	Levels of quasistatic magnetic fields (0.001–0.03 Hz) ranged 40 μT. Maximum levels of 120 μT found in DC powered locomotives. At frequencies <15 Hz, avg. magnetic field generated by Swiss AC powered locomotives was 10× greater than fields observed in Russian DC-powered trains.
Kaune et al., 2000	USA (Washington DC & Maryland)	Appliances (72 TV sets used by children to watch TV and 34 TV sets used to play video games)	GM: 0.0091 μT (ELF) and 0.0016 μT (VLF) for children watching TV programs. GM: 0.023 μT (ELF) and 0.0038 μT (VLF) for children playing video games
Kaune et al., 2002	USA	Electric appliances, headsets, home sewing machines	Fields near headsets at less than 60 Hz<0.01 μT. Home sewing machines produced magnetic fields >2.8 over ambient levels at the front surfaces of the lower abdomens of mothers.

that North American systems are associated with higher currents and accordingly with higher magnetic fields for given equipment. Nevertheless, levels of EMF vary from location to location, country to country, or continent to continent as a result of the power system used as well as the types of appliances and wiring practices.

III.C. Electric Appliances

EMF from particular appliances may vary greatly, depending on the way they are designed and manufactured. Surveys were conducted to measure fields from common appliances such as TV sets, hair dryers, stereo headsets, and sewing machines. Exposure levels were small compared to ambient levels [Kaune et al., 2000]. Measured magnetic fields in proximity of the above electrical appliances were elevated over the ambient when these devices were in use [Kaune et al., 2002]. Mean magnetic field measurements from appliances tended to be low in beds and high during the use of microwave ovens, coffee grinders, hair dryers, and electric shavers. In particular, magnetic fields measurements were highest from electrical appliances in occupational settings [Mezei et al., 2001].

III.D. Induced Electric Fields and Current Density

The relationship between environmental exposures and electrical quantities induced in the body is often termed *dosimetry* [Stuchly et al., 2002]. A few research laboratories have conducted extensive computations of induced electric field and current density in heterogeneous models of the human body in uniform EMF [Gandhi, 1995; Dawson et al. 1996, 1997, 1998; Dawson and Stuchly, 1998; Dimbylow, 1998, 2000; Stuchly et al., 2002; Kang and Gandhi, 2003].

Contact current may affect pluripotent progenitor cells in the bone marrow, the target cells for leukemia in adults and children. Small voltages present within the residence from residential grounding practices drive the contact current. Children may have differential sensitivity because of their smaller body dimensions and cartilaginous growth plates at the ends of their bones, both of which produce increased current density (and thus electric fields) in bone marrow compared to adults. In addition, children have active marrow in their hands and feet, both locations with small cross-sections [Kavet et al., 2000; Sastre and Kavet, 2002, Sheppard et al., 2002].

Dawson et al. [2001] created a model of a 5-year-old child by scaling the adult model purely for size but without adding voxels with marrow properties to the bones (such as the hand, wrist, and ankles) where children have red (blood-producing) marrow and adults do not. They noticed that electric fields in a model of child with anatomically correct marrow distribution would be higher, and the fields in an adult model exposed to 10 μA are roughly 25–50% of the values for the 5-year-old, depending on body location (the lower body impedance of an adult is more than offset by larger cross-sectional area).

Kowalski et al. [2002] calculated current density threshold for exciting the motor cortex area of the brain by means of the finite element method (FEM). Their values were 6 and 2.5 A/m2 at 2.44 kHz and 50 Hz, respectively.

Kang and Gandhi [2003] used the widely accepted 3-D impedance method to calculate the electric fields and current densities induced in a human model for an assumed but representative EAS device. It was shown that the two compliance testing methods give substantially different results for the induced 1-cm^2 area-averaged current densities as required by the ICNIRP guidelines [ICNIRP, 1998] and the 5-mm cube-averaged electric fields required for compliance testing against the proposed IEEE guidelines [IEEE, 1992]. The method of treating such exposures as multifrequency exposures give induced current density or electric current that may be up to twice as large as the approximate but simpler method of treating the highest of the pulses as a half sinusoid of the same duration and frequency. The authors suggest following the accurate method based on multifrequency analysis.

IV. EPIDEMIOLOGICAL STUDIES

The major objectives of most epidemiological studies are to determine whether a specific exposure or factor is likely to cause a given disease and to quantify the strength of the relationship. Two major study designs—the cohort and the case-control—are used to evaluate whether an exposure is linked with a given disease. In a cohort study, exposed and unexposed populations are ascertained, then followed up to compare risks of developing particular disease outcomes. In an ideal case-control study, cases are those who have developed a particular disease in a specified population during the study period, and controls are a random sample of those in the population who have not developed disease [Linet et al., 2003]. Most epidemiological studies are limited by the use of surrogate indicators rather than direct measurements of exposure. An epidemiological association, if found, might not be related directly to exposure; rather, it may be due to chance, confounding factors, or some unrecognized factors related to the way the data have been collected.

Consideration of the extent to which epidemiological studies may be successful in assessing EMF risk is essential when reviewing the literature. Most epidemiological studies reported in the literature have been criticized as having significant limitations, including failure to consider variability in exposure intensity, transients, intensity spikes, harmonics of the fundamental frequency, historical exposures, and concomitant exposures to other agents experienced in occupational settings.

Milham and Ossiander [2001] investigated the history of electrification and its association to cancer. They hypothesized that electrification of homes during the last century caused peak leukemia mortality among children 2–4 years of age. This occurred as domestic, urban, and rural reticulation of electric power was extended. This new age-related peak occurred in the UK in 1920s, the US in the 1930s, and in other countries as they reticulated power. The same time delay concept was clear between the wealthier and poorer neighborhoods in the US. The authors concluded that childhood acute lymphocytic leukemia (ALL) is attributable to residential electrification.

Health outcomes of particular interest in this section are childhood and adult cancer, as well as noncancer health effects, including reproductive effects, neurodegenerative diseases, suicide and depression, and cardiovascular diseases.

IV.A. Public Environments

Public environments in which EMF exposures can occur include residences, schools, and transportation facilities. The primary sources of residential and school fields are power lines, distribution lines, substations, wiring, grounding systems, and various electrical appliances. Sources of fields in trains and cars are mainly from the power lines supplying energy to the trains.

Li et al. [2003] investigated whether the age at cancer diagnosis was associated with residential exposure to magnetic fields. They compared average ages at diagnosis for cases of leukemia, brain tumor, or female breast cancer with elevated exposure (magnetic flux density 0.2 μT, or residential distance from major power lines 100 m) to average ages at diagnosis for cases with the same diagnoses but with a background exposure (< 0.2 μT or > 100 m from major power lines). They noted an association between magnetic field exposure and a greater mean age at diagnosis for brain tumors. The difference was greater for males than for females. No such phenomenon at a significant level was observed for leukemia, female breast cancer, or a random sample of general population. These phenomena suggest a delayed occurrence of brain tumors following a residential magnetic field exposure higher than background, and it deserves further investigation.

Numerous studies have showed that most high-level fields measured in houses are a result of proximity to power lines. Residential studies address the exposure of children and adults to EM fields as either population-based or case-control. A number of studies summarized here address the issue of residential EMF exposure.

1. Childhood Cancer and Leukemia

Childhood is a critical period of rapid cell growth, and the cancer development cycle is correspondingly much quicker than in adults. In addition, a child's immune system is underdeveloped, and melatonin production is lower. Melatonin is essential to the immune system, which protects the body from infection and cancer cells. Therefore, particular concerns are raised regarding children's safety from exposure to EMF from power lines, use of computers at homes and schools, and sitting too close to TV sets.

Childhood exposure to EMF has been studied intensively for many decades. However, research into this area gained momentum in 1979, when one of the first epidemiological studies [Wertheimer and Leeper, 1979] showed an association between exposure to EMF and cancer among children living near power lines. This study was followed by other studies of childhood cancer [Savitz et al., 1988; London et al., 1991; Feychting and Ahlbom, 1993; Olsen et al., 1993; Verkasalo et al., 1993; Linet et al., 1997; McBride et al., 1999; Schüz et al., 2001]. Although some studies have supported the findings of Werheimer and Leeper [Savits et al., 1988; London et al., 1991], more studies have failed to provide support for the hypothesis that EMF exposure increases the risk of childhood cancer. These studies include three collaborative population-based Nordic studies [Feychting and Ahlbom, 1993; Olsen et al., 1993; Verkasalo et al., 1993], a study in the US [Linet et al., 1997], two Canadian studies [McBride et al., 1999; Green et al., 1999], and a study in the UK [Skinner et al., 2002]. McBride et al. [1999] found that EMF exposures actually provide a significant protective effect against cancer for fairly raised field levels but not significantly protective for still higher fields.

Feychting et al. [2000] observed that children of fathers with occupational magnetic field exposure had a higher incidence of leukemia than expected. No link was found for childhood leukemia and maternal occupational magnetic field exposure. For maternal exposure, assessments were done for exposure both before and during pregnancy. Exposure assessment was based on actual measurements made with people with the same job titles. However, Infante-Rivard and Deadman [2003] reported that maternal occupational exposure to power frequency fields during pregnancy was associated with an excess incidence of childhood leukemia. Exposure assessment was based on actual measurements made with people with similar jobs.

Overall, the association between EMF exposure and childhood cancer remains inadequate and inconclusive (Table 3). Some studies have suggested a link between EMF and cancer, although the risks tend to be small by epidemiological standards, and were unable to exclude other environmental influences. While the level of epidemiological evidence in support of this association is limited, further research in this area is needed to clarify this issue.

TABLE 3. Epidemiological Studies of EMF and Childhood Leukemia

Investigator	Type; location; length; size	Risk measure	Outcome
Wertheimer and Leeper, 1979	CC; USA (Denver); <19 year; 155 cases/155 controls	OR WC: 2.98 (1.78–4.98)	Children had double or triple chance of developing leukemia or tumors of nervous system if they lived near transmission lines than those who did not.
Savitz et al., 1988	CC; USA (Denver); <15 year); ≥ 0.25 μT spot, 448 cases/466 controls	OR WC: 2.75 (0.94–8.04) MFM: 1.93 (0.67–5.56)	Increased cases of childhood cancer and leukemia associated with magnetic field exposures above 0.25 μT
London et al., 1991	CC: USA (Los Angeles); <10 year; ≥ 0.125 μT, 373 cases/348 controls	OR WC: 2.15 (1.08–4.26) MFM: 1.22 (0.52–2.82)	Largest study
Feychting and Ahlbom, 1993	PBCC; Sweden; <15 year; 38 cases/556 controls	RR WC: 3.8 (1.4–9.3)	39 leukemia and 33 CNS tumor cases; 3.8-fold increase of leukemia
Olsen et al., 1993	PBCC; Denmark; <15 year, 833 cases/1666 controls	OR WC: 6 (0.8–44)	Increased risk of leukemia among children with exposure to magnetic fields from high-voltage lines of 0.1 μT or greater
Verkasalo et al., 1993	PBCC; Finland; <17 year, 35 cases	OR WC: 1.6 (0.32–4.5)	1.6-fold increased risk of leukemia. Excess of brain tumor (OR = 2.3) found in boys (not girls) exposed to magnetic fields ≥ 0.2 μT.
Linet et al., 1997	CC; USA (9 states); <19 year; ≥0.3 μT, 24-h measurements, 1026 cases/1017 controls	OR WC: 0.98 (0.72–1.33) MFM: 1.24 (0.86–1.79)	No overall correlation between the level of field exposure and risk of ALL. Small increase in risk of ALL for children whose residences measured in very highest range of magnetic fields.

Investigator	Type; location; length; size	Risk measure	Outcome
Michaelis et al., 1998	PBCC; Germany (NW & Berlin); <15 year; 0.2 μT 24-h measurement, 176 cases/414 controls	OR MFM: 2.3 (0.8–6.7)	Association was statistically significant for children 4 years of age or less and for median nighttime magnetic field, but not for all children.
Li, et al., 1998	PBCC; Taiwan (North); 100 m from power lines	RR = 2.4	Children living in areas within 100 m of transmission line had leukemia rate 2.7 times higher than that of children nationwide.
McBride et al., 1999	CC; Canada (5 province); <15 year; ≥0.2 μT calculated, wire code, 48-h measurement 596 cases/648 controls	OR WC: 0.77 (0.37–1.60) MFM: 1.04 (0.69–1.57)	Elevated risk of ALL with high wiring configurations among residences of subjects 2 years before diagnosis/ reference date (OR = 1.72 compared with underground wiring, 0.54–5.45).
UK, 2000	CC; UK; <15 year; ≥0.4 μT calculated, 1094 cases/1096 controls	OR MFM: 1.68 (0.40–7.10)	This study used a complicated set of measurements and calculations to determine the arithmetic mean EMF exposure.
Schüz et al., 2001a	CC; Germany; 24-h measurements; residential exposure to 16.7 (railway frequency), 489 cases/1240 controls	OR <0.1 μT: 1 0.1–<0.2 μT: 0.31 (0.07–1.38) ≥0.2 μT: 1.91 (0.41–8.89)	A moderate but statistically nonsignificant association between magnetic field and childhood leukemia
Schüz et al., 2001b	PBCC; Germany (West); >0.2 μT; 24-h measurements, 514 cases/ 1301 controls	OR MFM: 1.55 (0.65–3.67)	Association between childhood leukemia and magnetic field exposure during the night (OR = 3.21 (1.33–7.80)

CC: case-control; PBCC: population-based case-control; WC: wire code; MFM: magnetic field measurement

2. Breast Cancer

Researchers hypothesize that EMF may be linked to breast cancer through the hormone melatonin. Feychting et al. [1998] conducted a case–control study based on people who had lived within 300 m of 220- or 400-kV power lines in Sweden between 1960 and 1985. For calculated magnetic field levels >0.2 μT closest in time before diagnosis, they estimated the risk ratio (RR) = 1.0 for women and 2.1 for men. Women younger than 50 years of age at diagnosis had an RR = 1.8. For women with estrogen receptor–positive breast cancer, the RR = 1.6, using the magnetic exposure >0.1 μT. Among estrogen receptor–positive women younger than 50 years at diagnosis, the RR increased to 7.4.

Gammon et al. [1998] conducted a case–control study to investigate the effects of electric blanket use. There were 2199 case patients under age 55 years that had been newly diagnosed with breast cancer between 1990 and 1992. The 2009 controls were frequency-matched to cases by 5-year age group and geographic area. A non-significant increased risk was observed in women who had ever used electrical appliances, especially blankets, mattress pads, or heated waterbeds. Similar findings were observed by other investigators [Verkasalo et al., 1996; Zeng et al., 2000; McElroy et al., 2001; Davis et al., 2001, 2002; Li et al., 2002; Schoenfeld et al., 2003; Kabat et al., 2003]. All the above studies provide evidence against a positive association between electric blanket or mattress cover use and breast cancer.

Erren [2001] reviewed this topic in detail. The author concluded that no human health risk has been proven. At the same time, the data was inadequate to confirm that some kind of effect could not exist.

An association between residential EMF exposure, including the use of appliances and breast cancer, is far from being established. Nevertheless, interest in this subject will continue based on the melatonin hypothesis.

IV.B. Occupational Environments

Occupational exposure environments are studied in the context of specific industries and workplaces, particularly in the electric power utility industry, where high exposure to EMF is likely. Workers can be exposed to EMF from the electrical systems in their building and the equipment they use. A variety of methods for exposure assessment are applied to studies in occupational environments. These methods range from job classification to modeling techniques, based on personal exposure measurements and occupational history. Occupational history is a collection of data for a study subject, which may contain information on jobs that the subject held during their employment. Such information is obtained by interviews or through various employment records. The information contains industry title, company name, description, and duration of the job. Medical records may also be obtained from clinics or disease registries.

Electrical appliances, tools, and power supplies in buildings are the main sources of EMF exposure that most people receive at work. People who work near transformers, electrical closets, circuit boxes, or other high-current electrical equipment may have high-field exposures. In offices, magnetic field levels are often similar to those found at homes, typically 0.5–4.0 milligause (mG). However, these levels may increase dramatically near certain types of equipment. In general, the literature is rich with more occupational studies investigating exposure of workers to EMF at various places using different techniques of evaluation.

1. Adult Cancers

Occupational exposure was studied, considering various health problems as well as adult cancers, including brain tumors and leukemia [Lin et al., 1985; Sahl et al., 1993; Thériault et al., 1994; London et al., 1994; Tynes et al., 1994; Savitz and Loomis, 1995; Coogan et al., 1996; Floderus et al., 1996; Fear et al., 1996; Miller et al., 1996; Feychting et al., 1997; Johansen and Olsen, 1998a,b; Savitz et al., 1999; Floderos et al., 1999; Carozza et al., 2000; Villeneuve et al., 2000, 2002; Minder and Pfluger, 2001; Navas-Acién et al., 2002; Willett et al., 2003], breast cancer among both men and women [Demers et al., 1991; Tynes et al., 1992; Coogan et al., 1996; Stenlund and Floderus, 1997; Johansen et al., 1998b; Petralia et al., 1998; Cocco et al., 1998; Floderos et al., 1999; Håkansson et al., 2002], lymphoma [Miller et al., 1996; Guenel et al., 1996; Villeneuve et al., 2000], lung cancer [Miller et al., 1996; Guenel et al., 1996; Savitz et al., Fear et al., 1996; 1997; Floderos et al., 1999; Håkansson et al., 2002], and other cancers [Firth et al., 1996; Miller et al., 1996; Guenel et al., 1996; Johansen et al., 1998b; Charles et al., 2003].

Sahl et al. [1993] studied utility workers at Southern California Edison. Comparisons in the cohort study focused on electrical versus nonelectrical workers, and exposure was characterized on the basis of job history. The authors noticed no difference in risk for brain cancer among electrical workers compared to the reference group. However, small but significant increases in brain cancer risk were observed for electricians (RR = 1.6) and plant operators (RR = 1.6)

Researchers from Canada and France [Thériault et al., 1994] conducted a study of 223,292 workers at three large utilities, two in Canada (Hydro Quebec and Ontario Hydro) and a national utility in France (Electricite de France). The result shows that workers with acute myeloid leukemia (AML) were about three times more likely to be in the half of the workforce with higher cumulative exposure to magnetic fields. In the analysis of median cumulative magnetic field exposure, no significant elevated risks were found for most types of cancer studied.

In 1995, Savitz and his group at the University of North Carolina carried out another major study [Savitz et al., 1995] involving more than 138,000 utility workers at five electric utilities in the US. Exposure was estimated by associating individual work histories with magnetic field measurements collected from 2842 work shifts. The researchers found that both total mortality and cancer mortality rose slightly with increasing magnetic field exposure. Meanwhile, leukemia mortality was not associated with indices of magnetic field exposure except for work as an electrician. In conclusion, the results of this study did not support any association between occupational magnetic field exposure and the risk of cancer, including leukemia.

Floderus et al. [1996] at the Swedish National Institute of Working Life reported an association between cancer and magnetic field exposure in a broad range. The study included an assessment of EMF exposure at 1015 different workplaces in Sweden and involved over 1600 people in 169 different occupations. The researchers reported an association between estimated field exposure and increased risk for chronic lymphocytic leukemia (CLL). In addition, an increased risk of brain tumors was reported for men under the age of 40 whose work involved an average magnetic field exposure of more than 2 mG.

Johansen and Olsen [1998a,b] conducted a study involving 32,006 men and women who had been employed at 99 electric utilities in Denmark, with employment history dating back to 1909. Cancer incidence was obtained from the cancer registry over the same period. The authors predicted that utility workers would have a higher incidence of cancer compared to the general population. They reported that the workers had slightly more cancer than expected from general population statistics, but there was no excess of leukemia, brain cancer, or breast cancer.

Recently, Willett et al. [2003] investigated whether the risk of acute leukemia among 764 adults is associated with occupational exposure to EM fields during 1991–1996. Risks were assessed using conditional logistic regression for a matched analysis. This large population-based case–control study found little evidence to support an association between occupational exposure to EM fields and acute leukemia. While an excess of acute lymphoblastic leukemia among women was observed, it is unlikely that occupational exposure to electromagnetic fields was responsible, given that increased risks remained during periods when exposure above background levels was improbable.

Most of the above studies concentrated on magnetic field exposures, assuming that they are the more biologically active components of the EMF and thus more likely to cause cellular damage. However, there are studies that indicate that electric field exposures may enhance cancer risk. Miller et al. [1996] examined the cumulative effects of both magnetic and electric field exposures on cancer incidence and reported a marked increase in leukemia risk. At the highest level of exposure to both magnetic and electric fields, OR increased from 3.51 to 11.2 when the researchers included the interaction of the combined effects of electric and magnetic fields. These investigators also reported an increase in the risk of all types of leukemia as well as some of the highest leukemia risks ever reported in a study of EMF and cancer. They also found evidence a of dose–response relationship, with the risk of leukemia increasing with cumulative exposure to electric fields (an effect noticeably absent with exposure to magnetic fields alone, both in this and in previous studies).

An elevated risk of leukemia was also seen among senior workers who spent the most time in electric fields above certain thresholds, in the range of 10–40 V/m [Villeneuve et al., 2000]. In a recent Canadian population-based control study, Villeneuve et al. [2002] conducted a study among men in eight Canadian provinces, for 543 cases of brain cancer confirmed histologically (no benign tumors included). Astrocytoma and glioblastomas accounted for over 400 of these. Population-based controls (543) were selected to be of similar age. They reported a nonsignificant increased risk of brain cancer among men who had ever held a job with an average magnetic field exposure >0.6 μT relative to those with exposures <0.3 μT. A more pronounced risk was observed among men diagnosed with glioblastoma multiforme (the most malignant of neuroepithelial neoplasms) (OR = 5.36).

There are rather notable differences in adult cancer studies with two kinds of results: (1) null association found in Southern California Edison workers [Sahl et al., 1993], in a study of US utility workers [Savitz et al., 1995], of Norwegian railway workers [Tynes et al., 1994], of electric utilities in Denmark [Johansen and Olsen 1998a,b]; and (2) mixed but in general positive results from studies of power-frequency magnetic fields [Thériault et al., 1994; Savitz and Loomis, 1995; Feychting et al., 1997; Floderos et al., 1999; Håkansson et al., 2002; Minder and Pfluger, 2001] and of electric field exposure [Guenel et al., 1996; Miller et al., 1996; Villeneuve et al., 2000, 2002]. The relative risks in the upper exposure categories were above 2.0 and for the more highly exposed groups between 1.1 and 1.3. Relative risks of this magnitude are below the level at which a casual association between EMF exposure and cancer can be assessed.

2. Other Effects

Various studies have been carried out to investigate the noncancerous health of people working or living near EMF exposure sources. The present review focuses on cardiovascular diseases [Savitz et al., 1999; Johansen et al., 2002; Sahl et al., 2002], neurodegenerative diseases [Sobel et al., 1995; Davanipour et al., 1997; Savitz et al., 1998a,b; Johansen and Olsen, 1998a,b], depression and suicide [Baris et al., 1996; Verkasalo et al., 1997; van Wijngaarden et al., 2000], and reproductive toxic effects [Wertheimer and Leeper, 1986, 1989; Dlugosz et al., 1992; Lindbohm et al., 1992; Juutilainen et al., 1993; Infante-Rivard, 1995; Lee et al., 2002; Li and Neutra, 2002; Blaasaas et al., 2002; Blaasaas et al. 2003], reflecting the preponderance of the literature on EMF health effects.

a. Cardiovascular Diseases

Savitz et al. [1999] investigated the risk of cardiovascular disease in a cohort of 139,000 male utility workers. Exposure was assessed according to the duration of employment in occupations with exposure to magnetic fields. Overall mortalities from cardiovascular disease were low. Sahl et al. [2002] found that men working longer in high-exposure occupations or as electricians, linemen, or power plant operators had no increased risk of dying from either acute myocardial infarction (AMI) or chronic coronary heart disease (CCHD) than did men who never worked in high-exposure occupations. Their study was based on cohort of 35,391 male workers at the Southern California Edison Company between 1960 and 1992. In addition, another study of electrical utility workers [Johansen et al., 2002] found no evidence that exposure to power-frequency fields was associated with heart disease.

b. Neurodegenerative Diseases

There could be moderate support for an association between occupational exposure to elevated levels of EMF and Alzheimer's disease (AD) and amyotrophic lateral sclerosis (ALS). A very large and detailed study conducted by van Wijngaarden et al. [2000] at the University of North Carolina uncovered what appears to be a distinct association between exposure to EMF and suicide among electric utility workers. A group of 138,905 male US electric utility workers from five companies were considered in the study. Electricians faced twice the expected risk of suicide. Linemen faced 1.5 times the expected risk. Meanwhile, suicides among power plant operators occurred at a rate slightly lower than expected. Baris et al. [1996] found no association between the suicide and exposure to EMF.

Ahlbom [2001] conducted a systematic review of the literature on neurodegenerative diseases and exposure to EMF. The author concluded, "For AD the combined data on an association with EMF are weaker than that for ALS. The association between suicide and EMF exposure was also weak. For depressive symptoms an assessment is more complex. For diseases such as Parkinson's, there is not enough information for an assessment."

Overall, currently available data suggest a weak association between EMF exposure and noncancer health effects. More research, particularly from large epidemiological studies, is needed.

c. Reproductive Toxic Effects

Wertheimer and Leeper [1986] investigated the relationship between use of electrically heated waterbeds and electric blankets and pregnancy outcome; especially, length of gestation, birth weight, congenital abnormalities, and fetal loss in Colorado. The study population consisted of 1806 (out of 4271) families in which a birth had occurred in two Denver-area hospitals in 1982. Seasonal patterns of occurrence of slow fetal development were observed among users of electric waterbeds and blankets, suggesting that use of such appliances at the time of conception might cause adverse health effects.

Dlugosz et al. [1992] investigated a possible relationship between the use of electric bed heaters and birth defects. They asked mothers of children born with cleft palate or neural tube defects if they had used an electric bed heater during the four months around the estimated date of conception. A total of 663 case mothers were matched with a similar number of control women who had given birth to children without birth defects. The comparison showed that mothers of children with birth defects were no more likely to have used an electric bed heater than other mothers.

Blaasaas et al. [2002, 2003] found little evidence that residence near power lines affected the risk of birth defects. The authors observed decreased risks of cardiac and respiratory defects and an increased risk of esophageal defects. They attributed that to a number of endpoints, including the imprecision in the calculations of the distance from the residence to the power line, and the limited information on pregnant women's change of residence. In a previous study, Blaasaas et al. [2002] found that the total risk of birth defects was not associated with parental exposure to 50-Hz EMF.

An exception to the lack of association of miscarriages and exposure to 50-Hz magnetic fields are three studies [Li et al., 2002; Lee et al., 2002; Li and Neutra, 2002]. They reported that high peak power-frequency exposures were associated with an increased risk of miscarriages in humans. The first population-based prospective cohort study [Li et al., 2002] was conducted among pregnant women within a large health maintenance organization. All women with a positive pregnancy test at less than 10 weeks of gestation and residing in the San Francisco area were contacted for participation in the study. All participants were also asked to wear a magnetic field-measuring meter for 24 hours and to keep a diary of their activities. Pregnancy outcomes were obtained for all participants by searching the health maintenance organization's databases, reviewing medical charts, and telephone follow-up. A total of 969 subjects were included in the final analyses. Miscarriage risk increased with an increasing level of maximum magnetic field exposure with a threshold around 16 mG. The risk associated with magnetic field exposure of 16 mG was 1.8. The risk remained elevated for levels of maximum magnetic field exposure of 16 mG. The association was stronger for early miscarriages (<10 weeks of gestation) (RR = 2.2) and among "susceptible" women with multiple prior fetal losses or subfertility (RR = 3.1). The findings provide strong prospective evidence that prenatal maximum magnetic field exposure above a certain level (possibly around 16 mG) may be associated with the risk of miscarriage.

The second case–control study [Lee et al., 2002] was conducted within a cohort of some 3400 pregnant women who were participating in a prospective reproductive health study. A sample was drawn of 531 women, of whom 219 allowed their exposures to be measured when they were or would have been 12 weeks pregnant, including 18 who miscarried. Of these women, 176 (10 with miscarriages) agreed to a second exposure measurement at 30 weeks of pregnancy, and they formed part of the study sample. The 328 women that were found to have miscarried (cases) and a random sample of 806 of those who had not miscarried were selected to provide controls. Of the five measures assumed to be associated with miscarriage, three were very weakly or not associated, while two were associated.

The third study [Li and Neutra, 2002] considered a cohort of 969 primiparous women who wore a meter for 24 hours for not more than 15 weeks after they had become pregnant. They found significantly higher risk of miscarriage for women exposed to magnetic fields of 1.6 μT or greater (RR > 2.2). Their findings of increased miscarriages are consistent with the findings of Wertheimer and Leeper [1986].

Following the publication of these two studies, Savitz [2002] commented on the same issue: "Prior to this research, the evidence supporting an etiological (causal) relation between magnetic fields and miscarriage could have been summarized as 'extremely limited.' With publication of these reports, I believe the evidence in support of a causal association is raised only slightly. These two new studies provide fairly strong evidence against an association with time-weighted average magnetic fields and moderately strong evidence for an association with other indices; both of these findings may be due to an artifact resulting from a laudable effort to integrate behavior and environment."

V. CELLULAR AND ANIMAL STUDIES

Laboratory studies provide another valuable source of information on the potential health risks of EMF. Laboratory studies on cells of whole organisms play a key role in evaluating the response of different systems of the body. Laboratory studies are easier to control and provide the opportunity to check whether EMF exposure causes cancer or other illnesses, something that is not possible with human volunteers. However, laboratory studies entail complications of their own. For example, how should results obtained in only one animal be relevant or extrapolated to humans?

Cellular and animal experiments have enhanced our understanding of the health consequences of EMF exposure. They generally examine the effects of EMF exposure on cells and various systems of the body, in particular the immune, nervous, and endocrine systems. These systems are largely responsible for maintaining the internal environment of the body.

During the past thirty years, a number of experiments and major scientific reviews have been conducted to assess the biological effects of EMF. Considering the interaction mechanism of these fields with biological systems, the effect of magnetic fields has been the central point of research, focusing primarily on fields of the magnitude encountered in everyday life (<100 μT).

V.A. Melatonin Hypothesis

One area attracting attention as a likely potential mechanism for EMF intervention in living organisms is consideration of a cancer-promoting effect of EMF by altered circadian rhythms of pineal activity and melatonin release. The "melatonin hypothesis," first proposed many years ago, explained how EMF exposure is related to certain kinds of hormone-dependent cancers, particularly breast cancer. Stevens [1987] found that EMF resulted in reductions in melatonin production by the pineal gland.

Kato et al. [1993], Wilson et al. [1999], and Huuskonen et al. [2001] reported that exposure to magnetic fields between 1 and 130 μT caused a decrease in melatonin levels in rats and hamsters. However, others studies found no evidence of any effect on melatonin in baboons, rats, and mice at fields between 1 and 100 μT [Rogers et al., 1995a,b; Mevissen et al., 1996; Löscher et al., 1998; Selmaoui and Touitou, 1999; Heikkenen et al., 1999; Fedrowitz et al., 2002; Bakos et al. 2002; Tripp et al., 2003].

Karasek and Lerchl [2002] reported the results of 60 independent assessments in animals of EMF exposure and nocturnal melatonin. 54% reported no effect or inconsistent effects, 43% reported decreased melatonin and 3% reported increased melatonin. Altogether, there is still not enough evidence to support the hypothesis that EMF exposure suppresses melatonin or causes an increase in cancer.

V.B. Genotoxicity

The weight of any positive association between EMF exposure and cancer depends on the ability of exposure to interact with genetic material to damage it, causing mutations that may lead to cancer. There have been many studies showing that EMF can damage DNA or induce mutations. Lai and Singh [1997] at the University of Washington, Seattle, observed an increase in double-strand DNA breaks in brain cells of rats being exposed to a 60-Hz magnetic field at flux densities of 0.25 and 0.5 mT. Wu et al. [1998] reported carcinogenic effects for both 50-Hz and 15.6-kHz magnetic fields on DNA damage/repair in the normal human amniotic fluid cell.

Other studies [Maes et al., 2000; Zmyslony et al., 2000] suggested that environmental EMF exposures at 1–500 μT flux density are unlikely to cause DNA damage. However, the second study [Zmyslony et al., 2000] did report that 7 mT caused DNA strand breaks when a strong oxidant was present. Also, environmental magnetic fields at 1–500 μT flux density were unlikely to induce carcinogenesis through a mechanism involving altered expression of the immediate early response genes [Yomori et al., 2002].

Khalil and Qassem [1991] reported chromosomal aberrations by exposing human lymphocyte cultures to a pulsing EM field (50 Hz, 1.05 mT) for various durations (24, 48, and 72 h). Suzuki et al. [2001] reported chromosome damage in the bone marrow cells of mice after exposing them to a high-intensity magnetic field (3–4.7 T) for 24–72 hours. However, other studies [Scarfi et al., 1994; Tateno et al., 1998; Maes et al., 2000; Nakahara et al., 2002] were unable to induce chromosomal aberrations even under relatively strong magnetic field exposure.

Singh and Lai [1998] found that EMF exposure caused DNA–protein and DNA–DNA crosslinks and increased apoptosis and necrosis in brain cells of the rat. They found also that pretreating rats with an iron chelator could block the effects of exposure on DNA. Svedenstal et al. [1999] observed an increase in DNA strand breaks in brain cells of mice after 32 days of exposure to magnetic fields at a low intensity of 7.5 μT. Ivancsits et al. [2002] reported that a 1-mT field caused DNA stand breaks if the exposure was intermittent, but not if the exposure was continuous. McNamee et al. [2002] investigated the effect of an acute 2-hour exposure of a 1-mT, 60-Hz magnetic fields on DNA damage in the brains of immature (10-day-old) mice. DNA damage was observed at 0, 2, 4, and 24 hours after exposure. No supporting evidence of increased DNA damage was detected.

It seems that the energy associated with EMF environmental exposures is not enough to cause direct damage to DNA; however, indirect effects are possible by changing cellular architecture and metabolic processes within cells that might lead to DNA damage. Together, there is negative evidence against DNA damage and chromosomal effects at the EMF environmental levels. Studies that do exhibit evidence for genotoxicity reported a mix of positive and negative results. In addition, there have been problems with replications of these findings.

V.C. Cell Functions

The literature has numerous reports on the effects of EMF exposure on ion transport, cell proliferation and differentiation, stress responses, and enzyme activity.

1. Intracellular Calcium

The phenomenon of Ca^{2+} efflux (release of calcium ions from a sample into a surrounding solution) from cells as a result of EM exposure is well known, especially in brain and lymphatic cells. Investigation has shown that EMF exposures at high flux densities influence the calcium efflux [Blackman et al., 1982, 1985; Ikehara et al., 1998; Galvanovskis et al., 1999; Pessina et al., 2001; Spadaro and Bergstrom, 2002; Teodori et al., 2002; Aldinucci et al., 2003a,b]. However, no change in calcium influx could be detected by other investigators [Ikehara et al., 2002; Obo et al., 2002]. Considerable attention has been given to explaining the mechanisms for the effects of exposure to a time varying magnetic field on the intracellular signaling pathway [Ikehara et al., 2002].

2. Cell Proliferation

Altered proliferation of cells in vitro as a result of EMF exposure has been observed in a number of studies [Antonopoulos et al., 1995; Katsir et al., 1998; De Mattei et al., 1999; Chen et al., 2000; Pirozzoli et al., 2003]. However, Aldinucci et al. [2003b] investigated whether static fields at a flux density of 4.75 T, generated by an NMR apparatus, could promote movements of Ca^{2+}, cell proliferation, and the eventual production of proinflammatory cytokines in human peripheral blood mononuclear cells (PBMC) as well as in Jurkat cells, after exposure to the field for 1 hour. The results clearly demonstrate that static NMRF exposure has no proliferative, activating, or proinflammatory effects on either normal or PHA-activated PBMC. Similar findings were observed by Supino et al. [2001] but at lower magnetic field densities (50 Hz, 20 or 500 μT) for different lengths of time (1–4 days).

3. Keratinocytes

The most numerous components of the epidermis are believed to manifest functional responses to physical stimuli. Shi et al. [2003] investigated whether EMF could act as an environmental insult to invoke stress responses in human keratinocytes using the 27-kDa heat shock protein (HSP27) as a stress marker. After exposure to 100 μT EMF from 20 minute to 24 hours, the isoform pattern of HSP27 in keratinocytes remained unchanged, suggesting that EMF did not induce the phosphorylation of this stress protein. EMF exposure also failed to induce the translocation of HSP27 from the cytoplasm to the nucleus. EMF exposure did not increase the abundance of HSP27 in keratinocytes. The authors found no evidence that EMF exposure enhanced the level of the 70-kDa heat shock protein (HSP70) in breast or leukemia cells, as reported previously. Overall, this study did not detect any of a number of stress responses in human keratinocytes exposed to power-line frequency EMF.

4. Ornithine Decarboxylase (ODC)

ODC is an enzyme that plays an important part in regulating cell growth through synthesis of polyamines necessary for protein and DNA synthesis. It is an enzyme activated during carcinogenesis. Studies were carried out to investigate whether there were effects on ODC from EMF exposure. An in vitro study [Litovitz et al., 1991] found increased ODC activity in three cell lines in response to a sinusoidal 60-Hz electric field (10 mV/cm). Stimulation in the activity of ODC in cultured cells by radio frequency radiation (RFR) with ELF modulation was also reported [Byus et al., 1988; Penafiel et al., 1997]. The results depended upon the type of modulation employed. These effects were noted only for certain modulations of the carrier wave, portraying the window effect (an effect that appears at a certain frequency but not at higher or lower frequencies). In addition, changes in ODC have also been reported from EMF exposure in vivo [Mevissen et al., 1995]. It is clear from the literature that a variety of in vitro studies have demonstrated that EMF exposure affects ODC activity and cellular proliferation, while exposure to fields below 0.1 mT have not been convincingly associated with adverse health effects.

5. Immune System

In most studies, EMF exposure appears to have no effect on the immune system. House et al. [1996] exposed mice and rats to 2, 200, and 1000 μT (60 Hz) continuously. No significant change in the distribution of lymphocyte subsets in the spleens of exposed mice was observed when compared with controls. They concluded that exposure of mice to linearly polarized, sinusoidal 60-Hz magnetic fields at strengths up to 1000 μT for up to 3 months did not significantly affect a broad range of immune effects or functions. In a study of human white blood cells, Aldinucci et al. [2003a] found no effect of a 4275-mT field on the inflammatory response of normal or leukemic cells. Onodera et al. [2003] reported that exposure of immune system cells to a 1-T field caused the loss of some cell types if the cells had been stimulated to divide, but no effect if the cells had not been stimulated into division. Ikeda et al. [2003], reporting on the exposure of human immune system cells to 2–500 μT fields (50 and 60 Hz linearly, elliptically, and circularly polarized), could not find any effects on the cytotoxic activities and the cytokines production of human PBMCs. However, Tremblay et al. [1996] found that 60-Hz linearly polarized, sinusoidal, continuous-wave magnetic fields (2, 20, 200, and 2000 mT) could induce immunological perturbations on cells of both natural and adaptive immunity in a dose-dependent fashion.

V.D. Animal Cancer Studies

There has been no absolute evidence in any study that low-level EMF alone can cause cancer in animals. This is supported by the findings of many studies [Sasser et al., 1996, 1998; Harris et al., 1998; Morris et al., 1999; Boorman et al., 1999; Galloni and Marino, 2000; Anderson et al., 2001; McLean et al., 2003]. Meanwhile, a few other studies show some influence—for example, Löscher et al. [1993] reported that magnetic fields of low-flux density (100 μT) promoted growth and size of mammary tumors but did not affect tumor incidence. Vellejo et al. [2001] reported that exposure of mice for 15 or 52 weeks to a 50-Hz field at 15 μT resulted in a significant increase in leukemia.

Animal studies presented mixed results, but no direct carcinogenic effects have been observed. Future research may focus on the role of EMF as a tumor promoter or copromoter. Only a limited number of in vivo studies suggest a positive relationship between breast cancer in animals treated with carcinogens and magnetic-field exposure at approximately 0.02–0.1 mT. According to Löscher [2001], one area with some laboratory positive evidence of cancer incidence could be in animals treated with carcinogens during an extended period of tumor development.

V.E. Noncancer Animal Studies

A number of noncancer studies were investigated for possible adverse effects of EMF exposure.

1. Behavioral Effects

There is insufficient evidence that EMF exposure at environmental levels causes behavioral changes in animals. Coelho et al. [1991] reported that exposure to electric fields at 30 kV/m (60 Hz) increased the occurrence of three out of ten categories of social behavior of baboons during a 6-week exposure, compared with equivalent rates observed in 6-week pre- and postexposure periods. Trzeciak et al. [1993] noted that exposure to magnetic fields (50 Hz, 18 mT) had no effect on open-field behavior of 10–12 adult male and female Wistar rats. But the investigators recommended the need for further studies to fully determine conditions under which an effect can be observed. Meanwhile, Sienkiewicz et al. [1998] reported that short-term, repeated exposure to intense magnetic fields might affect the behavior of mice. Mice were exposed each day to a 50-Hz magnetic field before being tested in a radial arm maze, a standard behavioral test of the ability of mice to learn a procedure for seeking food. Recently, Houpt et al. [2003] reported that exposure of rats to high-strength magnetic fields (7000 or 14,000 mT) caused behavioral changes within 5 minutes. Similar behavioral effects were observed by Lockwood et al. [2003] when mice were exposed to a 14.1 T field for 30 minutes. These effects, similar to the effects in rats [Houpt et al., 2003], may be the result of a vestibular disturbance caused by the magnetic field, according to the authors.

2. Reproductive and Development

There is no strong evidence of reproductive or developmental effects of exposure to magnetic fields in experimental animals. Studies using mice and rats have shown that exposure to magnetic fields results in fetal malformations [Chiang et al., 1995], skeletal malformations [Huuskonen et al., 1993; Mevissen et al., 1994], increase in placental resorptions [Juutilainen et al., 1997], and fertility [Al-Akhras et al., 2001]. However, Ryan et al. [1999] studied the effect of magnetic field (2, 200, and 1000 μT continuous exposure and 1000 μT intermittent exposure) on fetal development and reproductive toxicity in the rodent. There was no evidence of any maternal or fetal toxicity or malformation. Elbetieha et al. [2002] found that exposure of male and female mice to 50-Hz sinusoidal magnetic field (25 μT) for 90 days before they were mated with unexpected counterparts had no adverse effect on fertility and reproduction in mice. Other studies also have reported no major effects on reproduction and development in mice [Wiley et al., 1992; Kowalczuk et al., 1994; Ryan et al., 1996; Okazaki et al., 2002; Ohnishi et al., 2002; Chung et al., 2003].

Brent [1999] reviewed in vivo animal studies and in vitro tests, as well as the biological plausibility of the allegations of reproductive risks and concluded, “The studies involving nonhuman mammalian organisms dealing with fetal growth, congenital malformations, embryonic loss, and neurobehavioral development were predominantly negative and is therefore not supportive of the hypothesis that low-frequency EMF exposures result in reproductive toxicity.”

VI. CLINICAL STUDIES

Clinical studies carefully use screened volunteers who participate in double-blind studies, where appropriate, performed in a certified exposure facility. These studies investigate the effects of EMF exposure on various senses, hormones, and organs, such as hearing, the brain, the cardiovascular system, the immune system, melatonin, and the eyes. EMF effects might be studied safely and effectively in the laboratory with human volunteers in spite of limitations to the duration of exposure and types of tests that are performed. The focus in human studies is usually on the effects that occur within a time frame of minutes, hours, days, or perhaps weeks. Longer term studies with controlled exposure are difficult, if not impossible, to carry out with human volunteers in laboratory settings. The selection of physiological mechanisms for study is also limited to those that can be measured by noninvasive or minimally invasive procedures.

Various health effects are claimed by people as a result of EMF exposure, including headache, cardiovascular changes, behavioral changes, confusion, depression, difficulty in concentrating, sleep disturbances, decreased libido, and poor digestion. The main sources of information in this field are surveys of people and workers living close to potential sources of EMF, laboratory tests, and epidemiological data.

VI.A. Perception and Sensitivity

Exposure to electric fields, especially at low frequency (up to 300 Hz), can result in field perception as a result of alternating electric charge induced on the surface causing body hair to vibrate. Electrically excitable cells in the retina can be affected by current densities of 10 mA/m^2 or more, induced by low-frequency magnetic fields or directly applied electric currents but with no adverse health effects [ICNIRP, 1998a]. Most people can perceive electric fields greater than 20 kV/m, and a small percentage of people perceive field strengths below 5kV/m [Repacholi and Greenebaum, 1999; Christopher et al., 2002].

Humans experience flickering visual sensations caused by nonphotic stimulation such as pressure on the eyes and mechanical shocks. They are caused by induced currents in the retina, where the threshold at 20 Hz (maximum sensitivity occurs between 20 and 30 Hz) is about 20 mA/m^2. This is a level much higher than endogenous current densities in electrically excitable living tissues [Foster, 1996]. The effect observed in humans at the lowest magnetic field is a kind of visual sensation called a "magnetophosphene," where a flickering sensation is produced in surrounding vision by 50/60-Hz magnetic fields above about 10 mT. The effect is also connected to biomagnetic particles, which have been reported in the human brain [Adair, 1993].

A syndrome called "electrosensitivity" or electromagnetic hypersensitivity (EHS) initially appeared in Norway in the early 1980s among users of VDTs [Zisken, 2002]. The syndrome has included various nonspecific health symptoms such as skin reaction; electrophysiological changes in the central nervous system (CNS); and respiratory, cardiovascular, and digestive effects. Mueller et al. [2002] reported that some people appear to be able to detect weak (100 V/m and 6 μT) EMF, but the ability to detect the fields is unrelated to whether the person is electrosensitive.

Leitgeb and Schröttner [2003] considered an extended sample of the general population of 708 adults, including 349 men and 359 women aged between 17 and 60 years. Electrosensibility was investigated and characterized by perception threshold and its standard deviation. By analyzing the probability distributions of the perception threshold of electric 50 Hz currents, evidence could be found for the existence of a subgroup of people with significantly increased hypersensibility who as a group could be differentiated from the general population. The presented data show that the variation of the electrosensibility among the general population is significantly larger than has yet been estimated by nonionizing radiation protection bodies, but much smaller than claimed by hypersensitivity self-aid groups.

COMAR, a technical committee of the IEEE on Man and Radiation, released a technical information statement [COMAR, 2002] that describes EHS and summarizes recommendations from medical groups for helping people with EHS.

VI.B. Brain and Behavior

The CNS is a potential site of interaction with EMF because of the electrical sensitivity of the tissues. Lyskov et al. [1993a,b] performed spectral analysis of electroencephalography (EEG) recorded from volunteers exposed to a 45-Hz, 1.26-mT magnetic field. Significant increase in the mean frequency and spectral power were observed in the alpha and beta bands of the spectrum.

Studies conducted at 50 Hz on visual evoked potentials exhibited thresholds at flux densities of 60 mT [Silny, 1986]. No effect on visual evoked potentials was seen by Graham et al. [1994] while using combined 60-Hz EMF up to 12 kV/m and 0.03 mT, or by Crasson et al. [1996] when using intermittent, 50-Hz magnetic fields at 0.1 mT. However, Crasson et al. [1999] indicated that a 50-Hz at 0.1 mT magnetic fields may have a slight influence on event-related potentials and reaction time under specific circumstances of sustained attention.

Magnetic or electric fields in the occupational environment (up to 5 mT or 20 kV/m) are generally reported to have no or minimal effects on neurophysiologic (EEG rhythms and evoked potentials) or cognitive responses of human subjects [Cook et al. 1992; Graham et al. 1999; Crasson et al. 1999]. Preece et al. [1998] reported small reductions in attention and mnemonic aspects of task performance when volunteers were exposed to a 0.6-mT 50-Hz magnetic field. An insignificant effect on memory function has also been reported at a magnetic flux density of 1 mT [Trimmel and Schweiger, 1998]. On the other hand, Podd et al. [2002] failed to find any effects of the field on reaction time and accuracy in the visual discrimination task when using a 50-Hz, 100-μT magnetic field.

Cook et al. [2002] reviewed the behavioral and physiological effects of EMF on humans and concluded, "The variability in results makes it extremely difficult to draw any conclusions with regard to functional relevance for possible health risks or therapeutic benefits."

Although the evidence for an association between EMF exposure at levels lower than MPE values and brain activity is inconclusive, research on brain functions from prolonged exposure should be investigated in future research.

VI.C. Cardiovascular System

Heart rate, blood pressure, and the performance of ECG are commonly used to assess cardiovascular functions. Current densities of about 0.1 A/m^2 can stimulate excitable tissues, while current densities above about 1 A/m^2 interfere with the action of the heart by causing ventricular fibrillation, as well as producing heat. Korpinen et al. [1993] found no field-related changes in mean heart rate as a result of exposure to 50-Hz fields directly under power lines ranging from 110 to 400 kV. However, Sastre et al. [1998] and Sait et al. [1999] reported that exposure of human volunteers to 60-Hz magnetic fields (15 and 20 μT, respectively) caused changes in heart rate. Recently, Kurokawa et al. [2003b] reported the absence of effects on heart rate in human volunteers exposed to 50–1000 Hz magnetic fields at 20–100 mT for 2 minutes to 12 hours.

According to a review by Stuchly [1986], exposure of healthy male volunteers to 20-μT EMF at 60 Hz has been linked to a statistically significant slowing of the heart rate and to changes in a small fraction of the tested behavioral indicators. In another review, Jauchem [1997] concludes that no obvious acute or long-term cardiovascular-related hazards have been demonstrated at levels below current exposure limits for EMF.

VI.D. Melatonin in Humans

Several studies examining the suppression of human melatonin from exposure to EMF from VDTs [Arnetz and Berg, 1997] and electric utilities [Pfluger et al., 1996; Burch et al., 1998, 1999, 2000; Davis et al., 2001] have been reported. Many studies found no effect on melatonin levels among healthy volunteers exposed to fields at 1–200 μT [Graham et al., 1996, 1997, 2000; Hong et al., 2001; Crasson et al., 2001; Griefahn et al., 2001; Levallois et al., 2001; Youngstedt et al., 2002; Kurokawa et al., 2003].

Wood et al. [1998] reported that the nighttime melatonin peak was delayed by exposure to a 20-μT magnetic field, but that overall melatonin levels were not affected. Juutilainen et al. [2000] showed some ambiguous evidence for a decrease in nighttime melatonin production among female Finnish garment workers (who are exposed to power-frequency fields from sewing machines). Griefahn et al. [2001] reported that the effect of magnetic fields on melatonin secretion will most likely occur after repetitive exposures to intermittent fields. This conclusion was obtained after conducting a study on seven healthy young men 16–22 years of age.

Liburdy et al. [1993] indicated that melatonin reduces the growth rate of human breast cancer cells in culture, but a 1.2-μT (60 Hz) magnetic field can block the ability of melatonin to inhibit breast cancer cell growth. The above result was consistent with results in later reports [Harland and Liburdy, 2001; Blackman et al., 2001].

In a review, Karasek and Lerchl [2002] concluded, "At present there are no convincing data showing a distinct effect of magnetic fields on melatonin secretion in (human) adults." It is also not clear whether the decreases in melatonin reported in the positive articles are related to the presence of EMF exposure or to other factors.

VII. DISCUSSION

Current evidence from laboratory and epidemiological studies on the association between EMF exposure and cancer or other harmful health outcomes is inconsistent and inconclusive. Whereas early studies focusing on residents living near high-voltage transmission lines provided some evidence of a link between the risk of leukemia and EMF as characterized by Wertheimer and Leeper [1979], most of the subsequent studies using actual field measurements failed to confirm the initial findings.

Investigations of weak EM field (including ELF associated with cellular phones) effects on human physiology have yielded some evidence of effects in a number of different areas, such as heart rate variability, sleep disturbance, and melatonin suppression [NIEHS, 1999; Graham et al., 2000; Cook et al., 2002]. The lack of consistent positive findings in experimental studies weakens the argument that this association is actually due to EMF exposure only. Although experimental studies cannot be used to rule out the possibility of small risks, they can provide evidence of a positive association under certain exposure conditions. In order to achieve possible proof, there is a need for better EMF exposure assessments (including transients), increased cellular and animal studies that better simulate the effect on humans, and increased human population studies that evaluate exposures with adverse health outcomes.

Several major large-scale national and international programs and reviews were undertaken recently [NRC, 1997; NIEHS, 1998, 1999; NRPB, 2001; Henshow, 2001; Japan, 2001; Shaw, 2001; Erren, 2001; Kheifets, 2001; Ahlbom, 2001; IARC, 2002; Cook, 2002; Neutra et al., 2002]. In 1991, the National Research Council (NRC) convened an expert committee to review and evaluate the existing scientific information on the possible effects of EMF exposure on the incidence of cancer, on reproduction and developmental abnormalities, and on neurobiological response, as reflected in learning and behavior. The committee concluded in its 1997 report that the evidence does not support the notion that EMF exposure is a human health hazard (Table 4).

In the US, the mandate of the NRC committee was restricted in its scope; however, the National Institute of Environmental Health Safety (NIEHS) was charged to prepare and submit a wider evaluation of the potential human health effects from EMF exposure. In addition, the World Health Organization (WHO) has completed extensive reviews of related studies. Details of the above reviews are summarized in scientific journals [Repacholi, 1998; Havas, 2001], conference proceedings [Repacholi and Muc, 1999], and publications [NIEHS, 1998, 1999].

Evidence linking EMF to most cancers (except childhood and chronic lymphocytic leukemia, where the evidence has been characterized as "suggestive" or as "possibly carcinogenic" to humans) was deemed inadequate by NIEHS. WHO's International EMF Project reached similar conclusions [Repacholi and Muc, 1999]. The National Academy of Science concluded that there was no consistent evidence linking EMF and cancer [NRC, 1997]. Each of these reports noted a lack of studies properly designed to investigate this issue.

Childhood leukemia is the only cancer for which there is a statistically consistent evidence of an association with exposure to EMF above 0.4 μT. The evidence for a casual relationship is still inconclusive. The NIEHS concluded that there was limited evidence for an association with EMF exposure. Specifically, investigators found some evidence of an increased risk of leukemia associated with increased EMF exposure [NIEHS, 1999]. Similar conclusions were made by the NRPB [NRPB, 2001], the ICNIRP [Ahlbom, 2001], the International Agency for Research on Cancer (IARC) [IARC, 2002], and California EMF Program [Neutra et al., 2002]. The IARC has concluded that EMF exposures are possibly carcinogenic to humans, based on a consistent statistical association of high-level residential magnetic fields with an increased risk of childhood leukemia, by approximately a factor of two.

Most studies of adult cancers, particularly brain cancer, have been based on occupational groups, especially electrical workers with possibly high exposure. The few studies examining brain cancer and residential exposures found little or no evidence of association.

TABLE 4. Summary of Reviews of the Literature on Health Effects of EMF

Source	Evaluation		
NRC, 1997	Based on a comprehensive evaluation of published studies relating to the effects of power frequency electric and magnetic fields on cells, tissues, and organisms (including humans), the conclusion of the committee is that the current body of evidence does not show that exposure to these fields presents a human health hazard. Specifically, no conclusive and consistent evidence shows that exposures to residential electric and magnetic fields produce cancer, adverse neurobehavioral effects, or reproductive developmental effects.		
NIEHS, 1998	Function	Residential epidemiology	Occupational epidemiology
	Cancer	Limited evidence that ELF fields are carcinogenic to children. Inadequate evidence that ELF fields are carcinogenic to adults.	Limited evidence that ELF fields are carcinogenic to adults.
	Noncancer	Inadequate evidence that exposure to ELF fields are associated with depression. Weak evidence that short-term exposure to ELF fields suppresses melatonin and causes changes in sleep disturbances and heart-rate variability.	Inadequate evidence that exposure to ELF fields causes amyotrophic lateral sclerosis (ALS), cardiovascular disease, Alzheimer disease, adverse birth outcomes, reproductive effects, suicide, or depression.
	Experimental	In vivo	Strong evidence that exposure to ELF fields affects bone repair; weak evidence that exposure to ELF fields alter the levels of melatonin in rodents and no evidence in sheeps and baboons; weak evidence for neurobehavioral, neuropharmacological, neurophysiological in EMFs; no evidence for effects on the immune system; no evidence for reproductive and development effects of exposure to magnetic fields.
		In vitro	Moderate evidence for mechanically plausible effects of exposure to ELF fields greater than 0.1 mT; weak evidence for an effect of fields lower than approximately 0.1 mT.
	Summary: The final report said the ELF field exposure "cannot be recognized as entirely safe," but the probability that ELF EM fields are a health hazard is small at the moment.		

Source	Evaluation	
NRPB, 2001	Laboratory experiments have provided no good evidence that ELF EM fields are capable of producing cancer, nor do human epidemiological studies suggest that they cause cancer in general. There is, however, some epidemiological evidence that prolonged exposure to higher levels of power frequency magnetic fields is associated with a small risk of leukemia in children. In practice, such levels of exposure are seldom encountered by the general public in the UK. In the absence of clear evidence of a carcinogenic effect in adults or of a plausible explanation from experiments on animals or isolated cells, the epidemiological evidence is currently not strong enough to justify a firm conclusion that such fields cause leukemia in children. However, unless further research indicates that the finding is due to chance or some currently unrecognized artifact, the possibility remains that intense and prolonged exposures to magnetic fields can increase the risk of leukemia in children.	
Health Council of the Netherlands, 2001	The committee concludes that these recent meta-analyses show a consistent association between relatively high measured or calculated magnetic field strengths and an increased risk of childhood leukemia. However, from an epidemiological point of view, an association with a relative risk of <2 is to be considered weak. Furthermore, the committee does not think that either 0.3 μT (3 mG) or 0.4 μT (4 mG) should be regarded as a definite threshold field strength, above which the risk is suddenly increased.	
ICNIRP, 2001 Ahlbom et al., 2001	Cancer	Among all outcomes evaluated in epidemiologic studies of EMF, childhood leukemia in relation to postnatal exposures >0.4 μT is the one for which there is most evidence of an association. The relative risk has been estimated at 2.0 (95% confidence limit: 1.27–3.13) in a large pooled analysis. This is unlikely to be due to chance but, may be, in part, due to bias.
	Noncancer	On the basis of epidemiologic findings, evidence shows an association of ALS with occupational EMF exposure, although confounding is a potential explanation. Breast cancer, cardiovascular disease, suicide, and depression remain unresolved.
Japan EMF Research Program, 2001	It appears there is little possibility of finding new adverse health effects from EMF in the future. Very high-intensity EMF can have certain biological effects, but they occur only with EMF >10,000 times those found in real-world environments. Furthermore, even with the biological indicator that gave the positive results with 400 mT for 1 h, elongated exposure with 5 mT for 6 wk did not yield any effect. We conclude that adverse human health effects as a result of environmental power-frequency EMF either do not occur or that they are undetectable because they occur so rarely they cannot be separated by other processes.	

continues

TABLE 4. ***(continued)***

Source		Evaluation
Shaw, 2001		Evidence is lacking for a strong association between a woman's use of a VDT and fatal loss. Evidence is lacking for a strong association between a woman's use of a video display terminal (VDT) and adverse reproductive outcomes other than fetal loss, primarily a result of too few available data. The paucity of data on other parental EMF exposures and subsequent adverse outcomes of pregnancy limits drawing a valid scientific conclusion.
Erren, 2001		The data are consistent with the idea that exposures to EMF are associated with some increase in breast cancer risks, albeit that the excess risk is small.
Kheifets, 2001	Residential brain cancer	Inconsistent evidence that ELF cause childhood brain tumors. Little or no association between ELF field exposure and brain cancer.
	Occupational brain cancer	Slightly higher risk for electrical workers. A comparative analysis of electric utility workers also suggests a small increase in brain cancer risks.
		One note of the studies reviewed is large exposure miscalculations and the lack of a clear dose–response relationship in most individual studies.
Ahlbom, 2001		The overall conclusion is that there is weak support for the hypothesis that electric and magnetic fields (EMF) exposure increases the risk of suicide. Also, the support for the hypothesis of a relation between EMF and depressive symptoms is rather weak. For other diseases, such as Parkinson's, there is not enough information for assessment.
IARC, 2002		ELF magnetic fields are classified as "possibly carcinogenic" to humans based on epidemiological studies of childhood leukemia. Evidence for all other cancers in children and adults, as well as other types of exposures (i.e., static fields and ELF electric fields), was considered not classifiable due to either insufficient or inconsistent information.
Cook et al., 2002		The investigation of weak (<500 μT) ELF (0–300 Hz) MF exposure upon human cognition and electrophysiology has yielded incomplete and contradictory evidence that MFs interact with human biology. This may be due to the small number of studies undertaken examining ELF MF effects upon the human electroencephalogram (EEG) and the associated analysis of evoked related potentials (ERPs).
Neutra et al., 2002		EMFs can cause some degree of increased risk of childhood leukemia, adult brain cancer, Lou Gehrig's disease, and miscarriage. EMFs do not increase the risk of birth defects or low birth weight. EMFs are not universal carcinogens, since there are a number of cancer types that are not associated with EMF exposure. EMFs do not cause an increased risk of breast cancer, heart disease, Alzheimer's disease, depression, or symptoms attributed by some to a sensitivity to EMFs.

Studies examining health outcomes other than cancer do not provide sufficient evidence to support an association between EMF exposure and pregnancy outcomes, heart diseases, Alzheimer's disease, depression, or symptoms attributed by some to sensitivity. However, a number of epidemiological and experimental evidence suggests that relatively strong EMF can alter cardiac rhythm, which is not surprising in view of the electrical nature of the mechanisms controlling heart rate.

In evaluation of all epidemiological studies, researchers were particularly concerned with the methodological challenges, especially with respect to exposure control and assessment. The challenges include better knowledge about exposure metrics, periods of exposure, characterization of exposure sources, availability of population registry databases, and residential area measurements.

Laboratory research has given no consistent evidence that EMF at environmental levels for a substantial period can affect biological processes or cause cancer (Table 4). It is generally considered that EMF exposure does not possess enough energy to damage DNA directly, but there have been some reports in the literature of damage to DNA after exposure to EMF, and some of these reports are presented and discussed. Recent studies of disturbances in melatonin release in both animals and humans have been inconsistent. The NIEHS concluded that there was inadequate evidence for carcinogenicity in animals exposed to EMF.

In most cases, the NIEHS concluded that there was no solid evidence to suggest that EMF in environmental levels affects cells or systems. Two exceptions involved reports of weak evidence that EMF exposures contribute to behavioral, pharmacological, physiological, and biochemical changes in the nervous system and alter melatonin levels. EMF exposure, however, has been reported to enhance healing of damaged bones and is currently used in clinics for therapeutic purposes.

During the 1990s, Japan conducted an EMF research program comparable to the NIEHS EMF RAPID program (Table 4). The focus of this program was in vitro and in vivo testing for possible cancer effects (e.g., changes in gene expression, increased risks for tumors in animals). In 2001, the results of this research program were published [Takebi et al., 2001]. It is concluded that adverse human health effects as a result of environmental power-frequency EMF either do not occur or that they are undetectable because they occur so rarely that they cannot be separated by other processes.

On behalf of the California Public Utilities Commission, three scientists who work for the California Department of Health Services (DHS) reviewed the studies about possible health risks from EMF exposure [Neutra et al., 2002]. The reviewers are inclined to believe that EMF exposure can cause some degree of increased risk of childhood leukemia, adult brain cancer, and miscarriage. They believe that exposure to EMF is not a universal carcinogen and does not increase the risk of birth defects, low birth weight, depression, or heart diseases.

VIII. CONCLUSIONS AND RESEARCH NEEDS

Since 1979, there has been a flurry of scientific activity to evaluate the possibility that exposure to EMF from power lines and other sources may cause cancer. Overall, the currently available epidemiological and toxicological data do not provide clear evidence that EMF is associated with an increased risk of cancer, although there is some epidemiological evidence of linkages between EMF and childhood leukemia. There is also no convincing evidence from cellular and animal studies that EMF can directly damage DNA or promote tumor growth.

Looking to the future, further studies are required to address the following issues: (1) elucidation of the biophysical interaction mechanisms that may explain how the signal from the low-energy source could affect biological systems; (2) improved dosimetry to reduce uncertainties in exposure assessment; (3) in vitro and in vivo studies on genetic effects, melatonin secretion, and tumorigenesis (with particular emphasis on characterization of dose–response relationships under a range of exposure conditions); (4) understanding the neurophysiological implications of EMF; and (5) epidemiological studies to clarify the relationship between EMF and cancer in children, particularly leukemia.

A comprehensive research program that addresses these topics will require a transdisciplianry approach, involving specialists in EMF dosimetry, epidemiology, toxicology, and clinical research. This information will provide a firmer basis for assessing the potential health risks of EMF and for updating and harmonizing current protection guidelines. In addition, work is also needed to better understand public perception of EMF risks, which can inform the design of risk communication strategies related to the management of EMF health risks [see Part III of this three-part article, to appear in the next issue].

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Health Risks of Electromagnetic Fields. Part II: Evaluation and Assessment of Radio Frequency Radiation

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ABSTRACT: The increasing use of different radio frequency (RF)-emitting devices in residential and occupational settings has raised concerns about possible health effects of RF energy emitted by such devices. The debate about the potential risks associated with RF fields will persist with the prevalent network-connected wireless products and services targeting the marketplace for all kinds of consumer use. The aim of this article is to provide biomedical researchers with a review and critical evaluation of the current literature on acute and long-term health risks associated with RF radiation (RFR). Issues examined include safety standards for RFR; dosimetry and measurement surveys; and toxicological, epidemiological, and clinical studies of health outcomes that may be associated with RFR. Overall, the existing evidence for a causal relationship between RFR and adverse health effects is limited. Additional research is needed to clarify possible associations between RFR and biological effects noted in some studies. Particular attention should be directed toward long-term, low-level exposure to RFR.

KEY WORDS: standard development, RF dosimetry, epidemiology, cellular and animal studies, clinical studies

I. INTRODUCTION

The use of radio frequency (RF) equipment such as mobile phones, microwave ovens, RF heaters, base stations, radar installations, and telecommunications and broadcast

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facilities has led to widespread human exposure to radio frequency radiation (RFR), along with concerns about possible associations between RFR and adverse health outcomes, including cancer.

RF applications occupy a wide range of frequencies. For example, AM radio transmission uses 5–16 kHz, FM radio transmission uses 76–109 kHz, while 58–132 kHz and 8.8–10.2 MHz are used throughout the world for electronic article surveillance (EAS), radio frequency identification (RFID), and other security systems. Cellular and personal communications use frequencies between 800 MHz and 2 GHz. Emerging wireless-network-connected products and services may use frequencies up to 5 GHz. However, 2.45 GHz is reserved for industrial, scientific, and medical (ISM) applications (mainly microwave cooking).

Scientists, engineers, technicians, and physicians have been apprehensive about the potential hazards of RFR since World War II. There have been repeated calls for measures and tools that reduce RF exposure. During the past few decades, people have been especially concerned about the safety of radar equipment in the workplace and microwave ovens in their homes. Currently, it is wireless communication equipment (mobile phones) cradled next to the heads of millions of users that are of greatest concern [Habash, 2003].

Recent advances in wireless communication technologies have focused attention on the possible health consequences of mobile phone use. To date, there is limited information on the health risks stemming from the use of wireless equipment. As more products and services are developed and used in everyday applications, the potential for human exposure to RFR will increase.

The interaction of RF fields with living systems can be considered at the molecular, subcellular, cellular, organ and/or system level, as well as the entire body. Biological effects from exposure to RFR are differentiated into three levels: (1) high-level (thermal) effects, (2) intermediate-level (athermal) effects, and (3) low-level (nonthermal) effects.

This article traces the development of safety standards and exposure guidelines for RFR, along with the corresponding scientific basis for these recommendations. Our review highlights some of the uncertainties in the science underlying existing guidelines. Following a survey of RF sources and exposure scenarios, we examine toxicological, epidemiological, and human evidence on possible health effects associated with RFR.

II. RF EXPOSURE STANDARDS

Beginning in the 18th Century, scientific organizations were formed not only to address societal needs and concerns but also to resolve scientific disagreements. In the second half of the 19th Century and the first half of the 20th Century, a number of scientific and engineering organizations were formed to advise government agencies, industry, and others, with one of their primary tasks being the establishment of safety standards [Moghissi et al., 2003].

Scientists who are able to conduct a critical assessment of the outcomes base safety standards on a review of the relevant research. The exposure levels that are, or are considered likely to be, harmful to human health are determined. Such levels for human exposure to electromagnetic (EM) fields are generally called *maximum permissible exposure* (MPE) values, or *reference levels.* Guidelines recommending the limitation of RF exposure have been continually developing for over a decade (Table 1). MPE values from seven organizations were compared. Many countries develop their guidelines by either adopting or adapting the recommendations of major organizations such as the Institute of Electrical and Electronics Engineers (IEEE) [IEEE, 1992, 1999], the National Radiological Protection Board (NRPB) of the UK [NRPB, 1993, 1999], The Federal Communications Commission (FCC) of the US [FCC, 1996], the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [ICNIRP, 1998], Health Canada [Safety Code 6, 1999], and the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) [ARPANSA, 2002]. In 1999, the Council of the European Communities issued recommendations concerning exposure of the general public to EM fields, adopting the ICNIRP guidelines [CEC, 1999].

The exposure guidelines compared in this article are generally related in scope. All of the guidelines include separate exposure limits for various ranges of frequencies (although the defined limits for frequency groups differ). Each differentiates whole-body from partial-body exposure and considers exposure to multiple frequencies for comparison with the standard.

II.A. Safety Factors

MPE values usually include a safety factor that results in permissible exposures at levels well below those at which potentially hazardous effects may occur. The value of the safety factor reflects the extent of uncertainty about the lowest exposure level that could be hazardous, coupled with a desire to remain conservative with respect to health and safety. Improved knowledge about thresholds for hazardous effects may justify smaller safety factors [Sheppard et al., 2002]. Safety factors allow for extrapolating from animal studies to human, heat dissipation in the body, uncertainties in determining the precise threshold, and the hypothesis that some people may be more sensitive than others. Safety factor values between 10 and 1000 are often used. However, most of the known exposure standards have chosen a value of 50 for the public environment.

TABLE 1. Maximum Permissible Exposure (MPE) Values for RFR

Standard	Frequency range	Whole-body SAR (W/kg)		Local SAR in head (W/kg)		Local SAR in Limbs (W/kg)	
		Public	Occupational	Public	Occupational	Public	Occupational
ARPANSA	100 kHz–6 GHz	0.08 (6)	0.4 (6)	2 [10] (6)	10 [10] (6)	4 [10] (6)	20 [10] (6)
TTC/MPT	100 kHz–6 GHz	0.04 (6)	0.4 (6)	2 [10] (6)	8 [10] (6)		
Safety code 6	100 kHz–10 GHz	0.08 (6)	0.4 (6)	1.6 [1] (6)	8 [1] (6)	4 [10] (6)	20 [10] (6)
ICNIRP	100 kHz–6 GHz	0.08 (6)	0.4 (6)	2 [10] (6)	10 [10] (6)	4 [10] (6)	20 [10] (6)
FCC	100 kHz–6 GHz	0.08 (30)	0.4 (6)	1.6 [1]	8 [1] (6)	4 [10]+	20 [10] (6)+
NRPB	100 kHz–6 GHz	0.4 (15)		10 [10] (6)		20 [100] (6)	
ANSI/IEEE	100 kHz–6 GHz	0.08 (30)	0.4 (6)	1.6 [1] (30)	8 [1] (6)	4 [10] (30)+	20 [10] (6)

( ) Averaging time in minutes.
[ ] Averaging mass in grams.
+ in hands, wrists, feet and ankles.

II.B. Specific Absorption Rate

Specific absorption rate (SAR) is the rate at which RF energy is absorbed by the tissue and thus is a good predictor of thermal effects. SAR is defined as

$$\text{SAR} = \frac{\sigma|E|^2}{\rho} = c\frac{dT}{dt}$$

where E is the effective value of the electric field intensity in volts per meter (V/m), dT/dt is the time derivative of the temperature in Kelvin per second (K/s), σ is the electrical conductivity in siemens per meter (S/m), ρ is the mass density in kilogram per cubic meter (kg/m^3), *c* is the specific heat in joules per kilogram per Kelvin (J/kg K). The unit of SAR is in watts per kilogram (W/kg). SAR is the dosimetric measure that is used for extrapolating across species.

SAR calculations and estimates usually use many EM properties of biological tissues (e.g., complex dielectric constants and conductivity of different tissues), whose accuracy depends on their acquisition techniques, which are mostly in vivo.

There are two major types of SAR: (1) a whole-body average SAR; and (2) a local (spatial) peak SAR when the power absorption takes place in a confined body region, as in the case of a head exposed to a mobile phone. Whole-body SAR measurements are significant to estimate elevations of the core body temperature. As SAR increases, the possibility for heating and, therefore, tissue damage also rises. The whole-body SAR for a given organism will be highest within a certain resonant frequency range, which is dependent on the size of the organism and its orientation relative to the electric and magnetic field vectors and the direction of wave propagation. For an average human, the peak whole-body SAR occurs in a frequency range of 60–80 MHz, while the resonant frequency for a laboratory rat is about 600 MHz [Durney et al., 1986].

Both types of SAR are averaged over a specific period of time and tissue masses of 1 or 10 g (defined as a tissue volume in the shape of a cube). Averaging the absorption over a larger amount of body tissue gives a less reliable result. The 1-g SAR is a more precise representation of localized RF energy absorption and a better measure of SAR distribution. Local SAR is generally based on estimates from the whole-body average SAR. It incorporates substantial safety factors (for example, 20).

There are two local SAR safety limits applicable to mobile phones: 1.6 W/kg averaged over 1 g (SAR_{1g}) in North America; and 2 W/kg averaged over 10 g (SAR_{10g}), developed by the ICNIRP and accepted for use in Europe, Australia, Japan, and other parts of the world. Whether 1.6 W/kg or 2 W/kg is the correct limit for RF exposure remains controversial.

Exposure to RFR from mobile phones occurs in the region close to the antenna, the near field. However, exposure from other sources such as base stations occurs in the far field, which is often quantified in terms of power density, and expressed in units of watts per square meter (W/m^2). At lower frequencies, about 0.1–10 MHz, the energy absorbed is less important than current density and total current, which can affect the nervous system. There is an overlap region at the upper part of this range where either current density or energy absorption rate is the limiting quantity. The MPE values at the lower frequencies are concerned with preventing adverse effects on the central nervous system (CNS) and electric shock [Erdreich and Klauenberg, 2001]. Exposure limits at these lower frequencies also involve numerous technical issues, but are not the focus of this article.

II.C. Reconsideration of RF Safety Standards

The level of safety is the domain of regulators and others who derive their authority from a number of laws and statutes. The scientific community, the media, and ultimately the general public are often presented with contradictory information on the validity of standards originating from a variety of governmental and advisory organizations [Moghissi et al., 2003]. When scientists have considerable evidence of the health risks at high-intensity levels, yet minimal evidence of health risks at low levels, they have difficulty defining the safe levels. Current exposure guidelines are based on a scientific assessment of the relevant literature and may offer protection against the established health hazards of RF energy, which are thermal in nature.

Most of the RF standards reviewed had similar basic restrictions and almost similar MPE values. These similarities are related, in part, to the various dosimetric models used to relate field strengths to the basic restrictions. A comprehensive set of safety standards for all kinds of exposure to all frequency bands of RFR is not practical or probable. There are still many questions related to (1) main parameters such as SAR levels, duration of exposure, pulse effects, exposure geometry, modulation technique, and type of effect (thermal or nonthermal); (2) differences in absorption of RF energy by humans of different sizes and orientations; (3) complexity of measuring exposures, models, and statistical methods employed; and (4) incomplete discussion of research concerning possible long-term health effects. Although laboratory and epidemiological studies are available to address the likelihood of long-term effects, these data are not clearly described or specified in the standards. These questions require answers in order to define levels at which harmful effects can occur.

Do these exposure guidelines need to be reconsidered? It might be necessary because the guidelines are still intended basically to deal with thermal effects, not with energy at lower levels. However, during the past few years, there have been around 200 studies that suggest there may be health risks of RFR even at levels too low to cause heating of body tissue [Michaelson and Elson, 1996; Postow and Swicord, 1996]. There is not widespread acceptance of this fact in the scientific community, although many of these studies were included in the ICNIRP review. The reasons given are that the literature on nonthermal effects is complex, and the validity of the reported effects is poorly established. One reviewer [Foster, 2000] concludes, "Many reported effects find conventional explanation or simply disappear when follow-up studies are conducted under better controlled conditions." Nevertheless, the existence of health effects at low-level RFR should not be entirely ignored until more decisive information is provided through current and future research programs.

In addition, the guidelines were developed based on research studies conducted during and prior to the 1980s, when many of the current sources of RF energy (such as mobile phones) were not widely available. For example, the IEEE/ANSI C95.1, 1992 standard did not include any studies published after 1980s. However, the most recent review of literature for the purpose of formulating exposure guidelines has been undertaken by the ICNIRP [ICNIRP, 1998].

Another important issue is international harmonization, which refers to an international attempt to get various standard-setting bodies, health agencies, national governments, and international organizations to coordinate on health and safety standards for RFR. It does not necessarily mean that the world will have only one accepted RF standard, but it does mean that the basis for the differences is known. In this regard, Osepchuk and Petersen [2003] states, "The trend toward international harmonization of standards, at the moment, faces barriers posed by the regulations and rationales inherited from the USSR era. Many international meetings and the spread of electronic communication technologies will help eventually reach into Eastern Europe and the former communist countries. This will help in the movement toward international harmonization of standards."

III. DOSIMETRY AND MEASUREMENT SURVEYS

Dosimetry means measuring the dose of radiation emitted by a source. Dose measures that aspect of field exposure that is directly linked to the biological activity of the field, even though this aspect of the field may not directly cause the changes [Repacholi and Greenebaum, 1999]. Quantitative analysis of SAR in the human body exposed to EM radiation is referred to as *RF dosimetry* [Wang and Fujiwara, 2002]. RF dosimetry consists of the evaluation of incident and internal RF fields. These fields are either measured or calculated, depending upon the type and shape of the object [Durney and Christensen, 1999].

Measurement surveys provide procedures that are implemented in developing programs to protect workers and/or the public from exposure to RF energy above the allowable limits, as well as protect utilities from litigation or possible penalties. The first and foremost step is to survey any utility-owned or -leased sites that have transmitters, heat sealers, induction units, or any other devices that emit RF energy to determine if hazards are present. Taking an inventory of all site hazards is essential in order to follow the correct course of compliance action. During this surveillance phase, it is not always possible to specify the safety of a site. The only expected result is to show whether the site is complying with the adopted exposure guideline. The aim of this phase is to identify the highest fields and the safety relief program required. In addition, periodic site surveys are needed when RF sources are replaced or changed, in order to identify the effects that these changes have on RF coverage. Once identified, remedial action may be recommended to reestablish a state of optimal performance and ensure a safer environment.

III.A. Radio Base Stations

The fast growth of the cellular communication industry has resulted in the installation of a large number of base transceiver stations (BTSs), which are mounted on freestanding towers, rooftops, or the sides of buildings. A BTS refers to the antennas and their associated electronic equipment (equivalent to a radio station). A BTS may contain more than one transmitter, with the output of each transmitter fed to the antenna on top of the tower. BTSs usually transmit between less than a watt to as high as 500 watts per transmitter, depending on the location and type of antenna used for communication. While a typical BTS could have as many as 60–90 channels, not all of the channels would be expected to operate simultaneously, therefore reducing overall radiation.

The installation of BTS antennas frequently raises concerns about their human health impacts and safety, mostly for people who live in the vicinity of these sites. There might be circumstances where people could be exposed to fields greater than the MPE values. Because of building attenuation, levels of power density inside buildings at corresponding distances from the BTS antenna would be from 10 to 20 times smaller than on the outside. It is only in specific areas on the rooftop, depending on the proximity to the antenna, that the exposure levels are higher than those allowed by the RF protection guidelines. Accordingly, access to such locations should be restricted. Therefore, measurements in rooms exactly below roof-mounted antennas show power density levels lower than those at the roof top locations. This depends on the construction material. The level of power densities behind sector antennas is hundreds of times less than in front. Therefore, levels are too low in rooms located behind sector antennas. Figure 1 illustrates the conditions of RFR around a BTS.

The exposure situation around a typical BTS can be computed easily. The field strength data can then be analyzed with respect to possible conflicts with the available

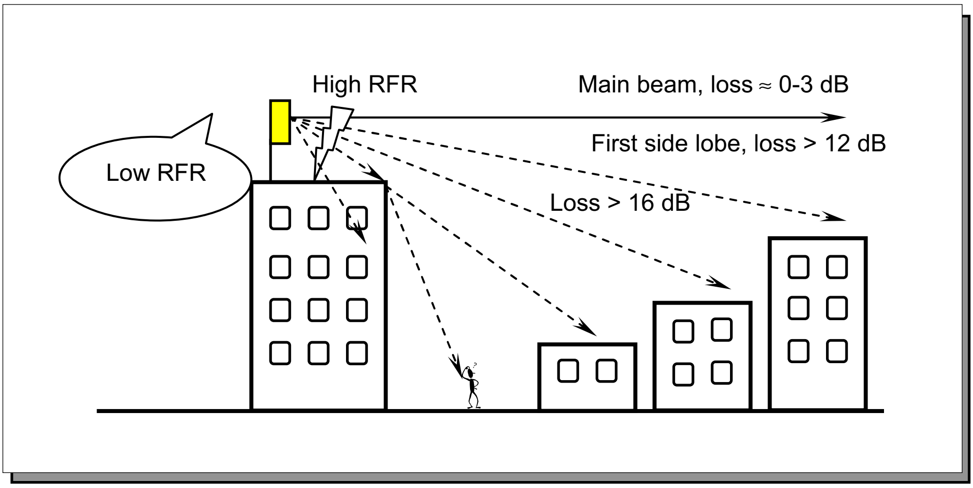

FIGURE 1. Conditions of RFR around a BTS.

guidelines for limiting RF exposure. In general, the maximum exposure levels near the base of a typical BTS antenna are actually lower than all recommended safety limits. These maximum exposure levels may occur only at limited distances close to the base of the BTS antenna. Typical safety distances for BTS range from 1 to 5 meters for one RF carrier in the direction of the main beam of the antenna. It is difficult to specify a typical BTS, because the configuration (i.e., service, power output, frequencies, antenna configuration) may vary considerably [Habash, 2001].

Measurements near typical BTSs have mostly shown that exposure levels are well within the widely promulgated guidelines [Thansandote et al., 1999; Mann et al., 2000; Bernardi et al., 2000a; Silvi et al., 2001; Anglesio et al., 2001; Cooper et al., 2002]. Bernardi et al. [2000a] indicated that the highest exposure could occur on nearby buildings directly in the antenna's main path. However, there may be circumstances where workers could be exposed to RF energy higher than the MPE values, generally on rooftops and close to antennas. The study provided theoretical evidence to suggest that the presence of reflecting and scattering structures, such as building walls, can have a profound influence on both the exposure and the power deposition inside the human body. For example, a subject standing on the rooftop at a distance of 8 m from the base of an antenna operating with 21 channels at a radiated power of 7.5 watts per channel would be exposed to spatial average and maximum incident power density of 0.6 and 1.3 W/m^2. If the human subject (1.8 m in height), with shoes, is facing the BTS antenna, a maximum SAR of 28 mW/kg, averaged over 1 g, would be found in the head. A corresponding average SAR of 0.63 mW/kg would be obtained for the whole body. If the same subject stands 2 m away from the building wall on a balcony located 30 m away, facing the antenna on the building next door, the maximum SAR in the head would be 69 mW/kg, and the SAR would be 2.4 mW/kg for the whole-body average. This means an increase of more than twofold in SAR.

A report by the Advisory Group on Non-Ionizing Radiation of the National Radiological Protection Boards [NRPB, 2001] gives advice on possible health effects of terrestrial trunked radio (TETRA), concluding that, "Although areas of uncertainty remain about the biological effects of low level RF radiation in general, including modulated signals, current evidence suggests that it is unlikely that the special features of the signals from TETRA mobile terminals and repeaters pose a hazard to health."

II.B. Broadcast Stations

Broadcast stations are usually located near densely populated areas so that large audiences can receive the signals. The radiation patterns from broadcast antennas are not as highly collimated as those from other RF sources, such as dish antennas used for satellite earth stations. Therefore, exposure to main-beam radiation intensities near the broadcast antenna is possible, especially if individuals are at eye level with the antenna bays (e.g., residents of high-rise buildings). Measurements near broadcast stations have shown significant differences in readings from indoors and outdoors, as well as from home and away. Exposures encountered by the public were well below the recommended MPE values [Hocking et al., 1996: McKenzie et al., 1998].

II.C. Traffic Radar Devices

Radiation levels associated with traffic radar devices vary according to the particular make and model of the radar gun. Usually radiation intensity drops to safe levels at distances of several meters from the antenna. Exposure to radiation from radar above the safety limits is most likely in the immediate vicinity of the antenna when it is stationary. A number of studies have been conducted concerning potential operator exposures to RFR emitted by traffic radars. Most of these studies measured some features of the emitted radiation intensity, and some of them measured levels of exposure at other locations away from the aperture of the antenna [Baird et al., 1981; Fısher, 1991, 1993; Lotz et al., 1995; Balzano et al., 1995a; Fınk et al., 1999].

II.D. RF Heaters and Sealers

RF ovens, dryers, sealers, and heaters provide the flexibility and speed to heat, dry, and cure a vast spectrum of products with demonstrated increases in productivity at lower costs. Such devices have been among the major sources of employee RF overexposure. Many studies [Stuchly et al., 1980; Bini et al., 1986; Olsen et al., 1993; Gandhi et al., 1997; COMAR, 1999] show that safe limits for RF energy from such devices are often exceeded for operators. In the frequency range of such equipment, fields may penetrate the human body and cause heating of internal tissues. Workers nearby may be unaware of their exposure to RF fields, because the fields can penetrate deeply into the human body without activating the heat sensors located in the skin.

II.E. Microwave Ovens

Given the popularity of microwave ovens, care must be taken to avoid exposure to the microwaves that heat and cook food. The main concern is leakage from the oven door. Surveys carried out to evaluate RF leakage levels from used microwave ovens [Moseley and Davison, 1989; Matthes, 1992; Thansandote et al., 1997] found that no models emitted microwave radiation in excess of the maximum allowed leakage (5 mW/cm^2). The levels of leakage were all well below the requirements of the regulations.

II.F. RF Environmental Levels

In the 1970s, the US Environmental Protection Agency (EPA) measured environmental field intensities at chosen locations in 15 US cities. RFR levels were measured at sites near single or multiple RF emitters—for example, at the bases of transmitter towers and at the upper stories (including the roof) of tall buildings or hospital complexes in the vicinity of transmitter towers. Janes et al. [1977] and Tell and Mantiply [1980] presented the results for those cities (a total of 486 sites). Those results were also summarized in Hankin [1985] and EPA [1986]. The exposure levels for all cities were largely below the MPE values. The major contributions to those exposure values were from FM radio and TV stations. These data are still used today because there have been no further measurements of RFR levels.

Hondou [2002] found that when hundreds of mobile phones emit radiation, their total power is comparable to a microwave oven or a satellite broadcasting station, and this level can reach the reference level for general public exposure (ICNIRP guideline) in daily life. This is caused by the fundamental properties of

EM fields—namely, reflection and additivity. However, Toropainen [2003] applied radio engineering principles to estimate the power density and SAR levels versus the number of mobile phones in screened environments occupied by humans. The author concluded that it is unlikely that exposure levels are exceeding the safe limits recommended by the ICNIRP due to multiple mobile phones users in train, elevators, cars, or similar environments.

II.G. Magnetic Resonance Imaging and Spectroscopy Systems

Magnetic resonance imaging and spectroscopy (MRI/MRS) systems are used in diagnostic medicine and display images in a format similar to computed tomography. Images of the body may be acquired and viewed with sub-millimeter resolution in the axial, coronal, or other planes. Applications of MRI are emerging in the areas of cardiology, neuroscience, image-guided surgery, and other minimally invasive procedures. Many safety issues, however, remain as possible concerns.

The proliferation of high-field (1–3 Tesla), very-high-field (3–7 Tesla), and ultra-high-field (>7 Tesla) whole-body MRIs calls for a review of the safety literature that can guide future studies of critical health-related issues [Kangarlu et al., 2000]. A number of computational reports have predicted the possibility of high SAR levels at high frequencies and formation of regions of high RF intensity (hot spots) at higher field strength [Gandhi and Chin, 1999; Collins and Smith, 2001; Kangarlu et al., 2003].

II.H. Whole-Body Dosimetry

Several investigations were performed to estimate the RF fields to which human subjects were to be exposed [Olsen and Griner, 1989; Adair et al., 1998, 1999, 2001]. Allen et al. [2003] reported the dosimetry performed to support an experiment that measured physiological responses of volunteer human subjects exposed to the resonant frequency for a seated human adult at 100 MHz. The dosimetry plan required measurement of transmitter harmonics; stationary probe drift; field strengths as a function of distance; electric and magnetic field maps at 200, 225, and 250 cm from the dipole antenna; and SAR measurements using a human phantom. Whole-body averaged SARs of 0.26, 0.39, and 0.52 W/kg result for the 4, 6, and 8 mW/cm^2 exposures. SAR values are just under, at, and just over the IEEE/ANSI C95.1 exposure standard [IEEE, 1992, 1999] of 0.4 W/kg. The authors presented also theoretical predictions of SAR using the finite difference time domain (FDTD) method, which predicted higher localized SAR in the head and spinal column and the highest SAR in the ankle.

II.I. In-Head Dosimetry of Mobile Phones

RFR is significant from mobile handsets because of the presence of the phone-transmitting antenna close to the head, neck, and hand of the user. The extent of exposure to RF energy from a mobile phone depends on the power of the signal the device transmits. Usually mobile phones transmit power in the range of 0.2 W to 0.6 W. Such power is limited by the cellular system (number of cells) and manufacturer specifications (design of the cellular phones casing, chassis length, electronic circuitry, channel access technique, antenna geometry, etc. [Kivekäs et al., 2003]). The second-generation (2G) systems, which are generally used at present, employ the time division multiple access (TDMA) technique. Under TDMA, subscribers share the radio spectrum in time domain, in which each user has full power during a defined time slot. The global system for mobile communication (GSM) standard employs TDMA technique with eight time slots. This means that the transmitter is only ever switched on for an eighth of the time. Therefore, the maximum average power output is 0.25 W for a 900 MHz GSM phone. Eight GSM phone users can share a pair of 200 kHz wide-band channels, because each user is given access only to a single 576-microsecond (μs) time-slot in a 4.6 millisecond (ms) frame, which is repeated 217 times a second. This 217-Hz cycle of power pulses is in the range of the normal bioelectrical functions both in and between cells, so it may induce low-frequency power surges, causing health problems. The 900-MHz RF carrier, with its lower average power output, likely does not cause health problems. Third-generation (G3) systems make use of the code division multiple access (CDMA) technique, in which all data are continuously transported at the same time, with a special code attached so that only the intended receivers can decode the messages.

Mobile phones yields numerically modeled brain SARs, which often exceed the 1.6 W/kg or 2 W/kg limits. This amount of power is lower than the body's normal resting metabolic output power [Moulder et al., 1999]. However, manufacturers should always be interested in reducing brain SAR as much as possible, not only because of possible health effects, but also to increase battery lifetime (the energy deposited in the brain drains the battery without any functional communication task).

Dosimetry of mobile phones targets SAR generated in the human head resulting from RFR, or the temperature rise from SAR as a heat source. The energy absorbed in the head is mainly due to electric fields induced by the magnetic fields generated by currents flowing through the feed point, along the antenna and the body of the phone. The RF energy is scattered and attenuated as it propagates through the tissues of the head, and maximum energy absorption is expected in the more absorptive high-water-content tissues near the surface of the head.

In-head dosimetry can be studied by evaluating mobile devices with a dummy head model called a *phantom,* a device that simulates the size, contours, and electrical characteristics of human tissue at normal body temperature. It is composed of a mannequin (solid shell) cut in half and filled with tissue-equivalent synthetic material solution, which has electrical properties of tissues. The phantom is typically set up in relation to other SAR measurement equipment. Measured pieces of equipment for this setup include a robot arm and a miniature isotropic electric field probe. A phone is positioned against the mannequin, operating at full power while the computer-controlled probe inserted into the tissue maps the electric fields inside. Computer algorithms determine the maximum electric field and then calculate a 1-g or 10-g average over a body to give a SAR value.

The local peak SARs differ depending on many factors, such as the antenna type, antenna radiation efficiency, antenna inclination with the head, distance of antenna from head, effect of the hand holding the handset, and the structural accuracy and resolution of the head model. Therefore, values of SARs are a function of various conditions set by each investigator. In other words, SAR is a result of a complex physical phenomenon of reactive coupling of the whole radiating structure with the human tissue. A significant contributor to the uncertainty in estimating SAR is the absence of a standard tissue averaging technique of the local SAR values over 1 or 10 g.

During the past few years, a considerable number of dosimetric studies have been performed for calculating or measuring power absorbed in phantoms simulating human heads exposed to RFR (Table 2). It is evident that many SAR values exceeded the MPE values [Dimbylow, 1993; Balzano, 1995b; Anderson, 1995; Okoniewski, 1996; Lazzi and Gandhi, 1998; Gandhi et al., 1999; Van Leeuwen et al., 1999; Wang and Fujiwara, 2000; Bernardi et al., 2000b; Van de Kamer and Lagendijk, 2002]. However, the temperature rise is far too small to have any lasting effects. Temperature measurements are significant only in case of high SARs. Increases in temperature (0.03–0.19 °C) are much lower than the threshold temperature for neuron damage (4.5 °C for more than 30 minutes), cataract induction (3–5 °C), and physiological effects (1–2 °C) [Anderson and Joyner, 1995; Van Leeuwen et al., 1999; Bernardi et al., 2000b]. Therefore, the temperature rise caused by mobile phone exposure has no effect on the temperature-controlling functions of the human brain. In fact, the thermostabilizing effect of brain perfusion often prevents temperature increase.

Moneda et al. [2003] verified by numerical calculation that the higher the frequency the more superficial the absorption. The numerical application manifests that the eyes, despite their small volume, absorb a considerable amount of the incident RFR, especially when the antenna is in front of the head, which is the most typical configuration related to use of 3G mobile phones. Another important issue raised by the authors is the enhancement of the hot spot near the center of the brain as the size of the head is reduced, which points to potential hazards to children using mobile phones.

Further dosimetrical studies are required, especially in areas related to numerical modeling of the energy absorbed in models of the human head, measurement of electrical properties of various head tissues, and SAR measurements.

TABLE 2. Summary of SAR Levels and Temperature Rise in Human Head

Investigator	Description of Source	SAR (W/kg)	Temperature Rise
Dimbylow, 1994	900 MHz: λ/4; 600 mW; 1.8 GHz; λ/4; 125 mW; calculated	For 900 MHz: SAR 1g = 2.17; SAR 10g = 1.82 For 1.8 GHz: SAR 1g = 0.7; SAR 10g = 0.48	
Balzano et al., 1995b	Motorola: 800-900 MHz; 600 mW and 2 W; measured	For analog (600 mW) classic antenna: SAR 1g = 0.2–0.4; flip antenna: SAR1g = 0.9–1.6; extended antenna: SAR1g = 0.6–0.8 For GSM (2 W) classic antenna: SAR1g = 0.09–0.2 flip antenna: SAR1g = 0.2–0.3 extended antenna: SAR1g = 0.1–0.2	
Anderson and Joyner, 1995	AMPS phones; 600 mW; 800/900 MHz	SAR in the eye: 0.007-0.21; metal-framed spectacles enhanced SARs in the eye by 9–29% SAR in brain: 0.12-0.83	Eye: 0.022 °C due to SAR 0.21 W/kg Brain: 0.034 °C due to SAR 0.83 W/kg
Okoniewski and Stuchly, 1996	Handset; 1W; 915 MHz; λ/4; calculated	SAR 1g = 1.9; SAR 10g = 1.4	
Lazzi and Gandhi, 1998	Handset; helical antenna 600 mW; 835 MHz 125 mW; 1900 MHz; calculated and measured	SAR 1g = 3.90 (calculated); SAR 1g = 4.02 (measured) SAR 1g = 0.15 (calculated); SAR 1g = 0.13 (measured)	

continues

TABLE 2. *(continued)*

Investigator	Description of Source	SAR (W/kg)	Temperature Rise
Gandhi et al., 1999	AMPS phones; 600 mW; 800/900 MHz; calculated and measured	SAR 1g > 1.6 unless antennas are carefully designed and placed further away from the head	
Van Leeuwen et al., 1999	Mobile phones; 250 mW; calculated	SAR 10g = 1.6	0.11 °C
Wang and Fujiwara, 2000	Portable phone: 900 MHz; 600 mW; helical antenna; calculated	SAR 1g = 2.10; SAR 10g = 1.21	
Bernardi et al., 2000	AMPS phones; 600 mW; 900 MHz; calculated	SAR 1g = 2.2–3.7	Ear: 0.22-0.43 °C Brain: 0.08 oC to 0.19 °C
Van de Kamer and Lagendijk, 2002	Dipole antenna; 250 mW; 900 MHz; calculated	Cubic SAR 1g = 1.72; arbitrary SAR 1g = 2.55 Cubic SAR 10g = 0.98; arbitrary SAR 10g = 1.73	

IV. EPIDEMIOLOGICAL STUDIES

There have been a number of epidemiological studies analyzing the relationship between exposure to RF fields and the development of cancer or other adverse health outcomes. With the increased interest in wireless networks and the safety concerns of this emerging technology, more studies can be expected.

IV.A. Occupational Exposure Studies

Occupational or controlled environments represent areas in which people are exposed to RFR as a result of their employment. The various health risks, including cancers, have been examined in occupational RF exposure studies. These included investigations involving radar and military personnel [Garland et al., 1990; Weyandt et al., 1996; Szmigielski, 1996; Reeves, 2000; Richter et al., 2000], police officers using traffic radar devices [Davis and Mostofi, 1993; Finkelstein, 1998], amateur radio operators [Milham, 1985, 1988], and telephone operators [Tynes et al., 1996; Grajewski et al., 1997]. A few epidemiological studies [Bini et al., 1986; Lagorio et al., 1997; Szmigielski et al., 1998; Irgens et al., 1999] have been performed with operators in industrial settings in order to assess specific problems that may arise, such as RF burns and/or burns from contact with thermally hot surfaces; numbness in hands and fingers and disturbed or altered tactile sensitivity; eye irritation; and warming and leg discomfort.

While some positive results have been reported in occupational studies of RFR, these studies provide no consistent evidence of an association between RFR and adverse health effects.

1. Navy Personnel and Military Workers

Robinette et al. [1980] conducted a study of mortality results on males who had served in the US Navy during the Korean War. They selected 19,965 equipment-repair men who had occupational exposure to RFR. They also chose 20,726 naval equipment-operation men who, by their titles, had lower occupational exposure to RFR as a control group. The researchers studied mortality records for 1955–1974, in-service morbidity for 1950–1959, and morbidity for 1963–1976 in veterans administration hospitals. Although exposures in the high-exposure group were assumed as 1 mW/cm^2, the three high-exposure categories included occasions of exposure in excess of 10 mW/cm^2. As a result, there were 619 deaths (3.1%) from all causes in the exposed group versus 579 deaths (2.8%) in the age-specific general white male population. The death rate from trauma was higher in the exposed than the control group, 295 (1.5%) versus 247 (1.2%). No difference on cancer mortality or morbidity was seen among the high- and low-exposure groups.

Szmigielski [1996] showed strong association between RF exposure and several types of cancer (including brain cancer and cancer of the alimentary canal) in a cohort of about 120,000 Polish military personnel, of whom 3% had worked with RF heat sealers. Exposure was determined from assessments of field levels at various locations. The study did not consider the length of time at the location, the nature of the job, or the number of cases observed.

Groves et al. [2002] have reported the outcome of a 40-year follow-up of mortality from cancer and other causes in the same group of Navy personnel during the Korean War. The results were similar to those of Robinette et al. [1980], confirming that radar exposure had little effect on mortality.

2. Traffic Radar Devices

Davis and Mostofi [1993], in a brief communication, reported six cases of testicular cancer in police who used handheld radar between 1979 and 1991 among a cohort of 340 police officers employed at two police departments within contiguous counties in the north-central United States. The six cases had been employed as police officers as their primary lifetime occupation, and all had been exposed to traffic radar on a routine basis. The mean length of service prior to testicular cancer diagnosis was 14.7 years, the mean age at diagnosis was 39 years, and all had used radar at least 4.5 years before the diagnosis.

Fınkelstein [1998] presented the results of a retrospective cohort cancer study among 22,197 officers employed by 83 Ontario police departments. The standardized incidence ratio (SIR) for all tumor sites was 0.90. There was an increased incidence of testicular cancer (SIR = 1.3) and melanoma skin cancer (SIR = 1.45). No information about individual exposures to radar devices was provided.

3. RF Heat Sealers

Lagorio et al. [1997] reported higher cancer mortality among Italian plastic ware workers exposed to RFR generated by dielectric heat sealers for the period 1962–1992. Six types of cancers were found in the exposed group. The standardized mortality ratio (SMR) analysis was applied to a small cohort of 481 women workers, representing 78% of the total person-years at risk. Mortality from malignant neoplasms was slightly elevated, and increased risk of leukemia was detected. The all-cancer SMR was higher among women employed in the sealing. Exposure assessment was based on the time assigned on jobs. Exposure to RFR was based on a previous survey, which showed that the radiation exceeded 1 mW/cm^2. The work area also included exposure to chemicals associated with cancer (solvents and vinyl chloride), which may have impacted the results.

4. Telecom Operators

In Norway, Tynes et al. [1996] studied breast cancer incidence in female radio and telegraph operators with potential exposure to light at night, RFR (405 kHz–25 MHz), and extremely-low-frequency (ELF) fields (50 Hz). The researchers linked the Norwegian Telecom cohort of female radio and telegraph operators working at sea to the Cancer Registry of Norway to conduct their study. The cohort consisted of 2619 women who were certified to work as radio and telegraph operators. The incidences of all cancers were not significant, but an excess risk was seen for breast cancer. They noted that these women were exposed to light at night, which is known to decrease melatonin levels, an expected risk factor for breast cancer.

IV.B. Public Exposure Studies

Studies of public exposure to RFR have focused on two common RF field sources: radio and TV transmitters [Hocking et al., 1996; Dolk et al., 1997a,b; McKenzie et al., 1998; Michelozzi et al., 1998, 2002; Cooper et al., 2001; Hallberg and Johansson, 2002] and mobile phone use [Funch et al., 1996; Rothman et al., 1996; Hardell et al., 1999, 2000, 2001, 2002a,b, 2003a,b; Deyer, 1999; Muscat et al., 2000, 2002; Oftedal et al., 2000; Owen, 2000; Inskip et al., 2001; Stang et al., 2001; Auvinen et al., 2002, Warren et al., 2003].

1. Radio and TV Transmitters

An association between proximity of residences to TV towers and increased incidence of childhood leukemia was found in an Australian study conducted by Hocking et al. [1996]. The researchers studied the leukemia incidence among people living close to TV towers (exposed group) and compared this to the incidence among those living farther from the towers (unexposed or control group). People were assigned to one of the two groups based on data from the New South Wales Cancer Registry and their accompanying address. The Hocking study concluded that there was a 95% increase in childhood leukemia associated with proximity to TV towers. No such association was found between RFR emitted by the TV towers and adult leukemia. McKenzie et al. [1998] repeated the Hocking study, using more accurate estimates of

RFR at the same area and at the same time period. They found increased childhood leukemia in one area near the TV antennas, but not in other similar areas near the same TV antennas. They found no significant correlation between RF exposure and the rate of childhood leukemia. They also found that much of the "excess childhood leukemia" reported by the Hocking study occurred before high-power 24-hour TV broadcasting had started.

In Italy, Michelozzi et al. [1998, 2002] conducted a small-area study to investigate a cluster of leukemia near a high-power radio transmitter in a peripheral area of Rome. The leukemia mortality within 3.5 km (5863 inhabitants) was higher than expected. The excess was due to a significant higher mortality among men (seven cases were observed). Also, the results showed a significant decline in risk with distance from the transmitter, but only among men—no association for women, and a nonsignificant decrease in risk for both sexes combined. For childhood leukemia, based on eight cases, there was a significant trend of risk decreasing with distance.

2. Mobile Phones

Most of the mobile phone studies (Table 3) show no increased incidences of brain tumors among mobile phone users (analog or digital). Furthermore, there was no relationship between brain tumor incidences and duration of mobile phone use. Hardell et al. [1999, 2000, 2001] studied more than 200 brain tumor patients aged 20–80 years in two regions in Sweden. In the first study, Hardell et al. [1999] conducted a case-control study (1994–1996) using patients diagnosed with brain tumors who were alive at the time the study commenced. Mobile phone usage and the type of phone (analog or digital) were determined by questionnaire. Dose–response assessment provided no evidence of an association between RFR and brain cancer. However, the small number of cases and the short period of exposure to RFR from mobile phones limit the opportunity to identify an increased risk. The second and third studies [Hardell et al., 2000, 2001] were similar in design to the previous study and covered a wide range of exposures from other RF sources in addition to mobile phones. An association was reported between the use of analog phones and benign brain tumors for >1 year (OR = 1.3), >5 years (OR = 1.4), and >10 years (OR = 1.8). A multivariate analysis revealed no statistical significance and lower risk for the >5 years (OR = 1.1) latencies.

Hardell et al. [2002a] conducted another case-control study of patients with malignant or benign cranial tumors diagnosed in Sweden from 1997 to 2000. They used a postal questionnaire supplemented by phone interviews. Information on mobile phones was divided into analog (450 or 900 MHz), digital, and cordless phones. The analysis assessed type of phone; duration of use; time since first use; and site, history, and laterality of tumor. A small but statistically significant increased risk of

TABLE 3. Summary of Epidemiological Studies of Mobile Phones and Cancer Risk

Investigator	Description	Risk Measure	Outcome
Brain Tumors			
Hardell et al., 1999	PBC: Sweden (1994–1996) (GSM/NMT phones) 209 brain tumor cases 425 controls	OR = 0.98 (0.69–1.41) Same side of the head: OR = 2.42 (0.97–6.05)	Right-brain tumors for users who used the phone at their right ear. Stronger for temporal or occipital localization of the tumor on right side (only for analog phones). Temporal or occipital localization of the tumor on the same side as phone use for the left side use.
Muscat et al., 2000	CC: USA (1994–1998) 469 brain cancer 422 controls	OR = 0.85 (0.6–1.2)	No significant association between primary brain cancer and years of mobile phone use, number of hours of use per month, or cumulative number of hours of use.
Inskip et al., 2001	CC: USA (1994–1998) 489 Glioma 197 meningiomad 96 acoustic neuroma 799 controls	OR = 1.0 (0.6–1.5) Glioma: 0.9 (0.5–1.6) Meningioma: 0.2 (0.3–1.7) Acoustic neuroma: 1.4 (0.6–3.5)	The results do not support the existence of an association between mobile phone use and certain cancers (glioma, meningioma, or acoustic neuroma). There was no difference for side of head.
Johansen et al., 2001	CE: Denmark (1982–1995) 420,095 users from two operators 3,391 cancers 3,825 expected	SIR = 0.89 (0.86–0.92) Brain: SIR = 0.95 (0.81–1.12) Salivary gland: SIR = 0.72 (0.29–1.49) Leukemia: SIR = 0.97 (0.78–1.21)	No relationship between brain tumor risk and RF dose compared by duration of phone use, date since first subscription, age at first subscription, or type of phone used.
Auvinen et al., 2002	CC: Finland (1996) 398 brain tumors 198 gliomas 34 salivary gland 5 controls per case	Brain tumor: OR = 1.3 (0.9–1.8) Salivary gland: OR = 1.3 (0.4–4.7) Gliomas: OR = 2.1 (1.3–3.4) (analog) Gliomas: OR = 1.0(0.5–2.0) (digital)	No clear association between use of mobile phones and risk of cancer has been provided. Gliomas were associated with use of analog but not digital phones.
Muscat et al., 2002	CC: USA (1997–1999) 90 acoustic neuroma 86 controls	Up to 60 h of use: OR = 0.7 (0.2–0.6) 3–6 years of use: OR = 1.7 (0.5–5.1)	Although there was an elevated risk with 3 or more years of phone use, these longer-term users were also the most infrequent users, and there was no association with cumulative use.

TABLE 3. (continued)

Investigator	Description	Risk Measure	Outcome
Hardell et al., 2002a	CC: Sweden (1997–2000) 1303 brain tumor cases and controls	For >1 year latency Analog: OR = 1.3 (1.02–1.6) Digital: OR = 1.0 (0.8–1.2) Cordless: OR = 1.0 (0.8–1.2) Acoustic neuroma: OR = 3.5 (1.8–6.8)	Significant association for analog and cordless phones and all tumors. No evidence of dose response by duration of phone use.
Hardell et al., 2002b	CC: Sweden (1997–2000) Malignant tumors 588 cases 581 controls	Analog: OR = 1.85 (1.16–2.96) Cordless: OR = 1.46 (0.96–2.23)	Statistically significant results for analog and cordless phones. Multivariate analysis not significant. No increased risk with longer duration, except for cordless.
Hardell et al., 2003a	CC: Sweden (1997–2000) 1429 cases 1470 controls Questionnaire	Cordless: OR = 1.5 Analog: OR = 3.7	Some surprising statistically significant results. For instance, OR for cordless phones for astrocytomas of 1.5 is unusual, given that cordless phones, which use extremely low power in Sweden, have never been implicated in brain tumors.
Hardell et al., 2003b	CC: Sweden (1960–1979) Vestibular schwannoma (VS)	For >1 year latency Analog: OR = 3.45 (1.77–6.76) Digital: OR = 1.21 (0.66–2.22) Cordless: OR = 1.03 (0.62–1.72)	A significant increased risk for VS was found for analog phone users. Digital and cordless phones also revealed an increased but not significant risk.
Warren et al., 2003	CC: USA (1995–2000) 18 cases 192 controls Intratemporal facial nerve (IFN) tumor	OR = 0.6 (0.2–1.9)	Regular cellular telephone use does not appear to be associated with a higher risk of IFN tumor development. The short duration of widespread cellular telephone use precludes definite exclusion as a risk for IFN tumor development.
Melanoma of the Eye			
Stang et al., 2001	CC: Germany (1994-1997) Uveal melanoma 118 case 475 control	OR = 3.0 (1.4–6.3)	Association between RF exposure from mobile phones and uveal melanoma.

OR: odds ratio; CC: case control; CE: case ecological; PBC: population-based control any type of brain tumor was seen with the use of analog phones (OR = 1.3, 95% CI, 1.02–1.6), increasing to 1.4 with more than 5 years' latency and 1.8 with over 10 years' latency. For digital phones, there was no increased risk. For cordless phones, there was no association in general (OR = 1.0, 0.8–1.2). The highest risk was for acoustic neurinoma (OR = 3.5, 95% CI, 1.8–6.8) with the use of analog phones. In a following article [Hardell et al., 2002b] based on modified analysis of the data for malignant tumors already presented [Hardell et al., 2002a], the authors concluded that a significantly increased risk was seen with ipsilateral use of analog phones. Data on acoustic neuroma and benign and malignant brain tumors from the previous studies [Hardell et al., 2002a,b] was reported recently [Hardell et al., 2003a,b] with different analysis. The results show increased incidence of acoustic neuroma than other brain tumors in the Swedish Cancer Registry between 1980 and 1998.

Other studies have failed to find a relationship between phone use and the location and incidence of brain tumors [Muscat et al., 2000, 2002; Johansen et al., 2001; Inskip et al., 2001; Auvinen et al., 2002]. Muscat et al. [2000] identified 469 men with primary brain cancer in five US medical centers. They were studied with 422 matched controls. The risk of brain cancer was compared according to the use of mobile phones in hours per month and years of use. Median monthly hours of use were 2.5 for cases and 2.2 for controls. Compared with controls who never used mobile phones, there was no increased risk of brain cancer, with OR of 0.85 (0.6–1.2). There was no increased risk for heavy users (more than 10 hours a month) compared with light users (less than 0.7 hours a month). The study found that among brain cancer cases, cerebral tumors occurred more frequently on the side of the head where cellular phones had been used (26 versus 15 cases). However, in cases of temporal lobe cancer, a greater proportion of tumors occurred in the opposite side of the head (9 versus 5 cases).

Johansen et al. [2001] used information from mobile phone companies to identify all users of mobile phones in Denmark. This identified 420,095 persons whose mobile phone use could be linked to a Danish cancer registry operating since 1942, with information on cancer diagnosis. There was no increased risk of any cancer associated with mobile phone use in men or women, in particular brain and salivary gland cancers and leukemia. Also, there was no raised risk for any type of brain or nervous system disorder.

Inskip et al. [2001] conducted a prospective case-control study of 792 patients with brain tumors and 799 matched controls in the US between 1994 and 1998. Of the controls, 29% reported using a mobile phone more than five times. There was no relationship between any tumor type or all tumors and the use of mobile phones. Also, there was no relationship between the side on which the tumor occurred and the side on which the mobile phone was most often used.

Muscat et al. [2002] conducted a case-control study for 90 patients with histologically confirmed acoustic neuroma diagnosed between 1997 and 1999 in New

York. Controls were 86 in-patients with a variety of nonmalignant conditions, matched by age, sex, race, and hospital of admission. A structured questionnaire identified use of mobile phone. The risk of acoustic neuroma was unrelated to the frequency and duration of mobile phone use, with OR of 1.7 (95% CI). There was no relation with cumulative use or with increasing levels of RF exposure.

In another case-control study, Auvinen et al. [2002] identified 398 subjects with newly diagnosed brain tumors and 34 salivary gland cancers in patients aged 20–69 years in Finland in 1996. Approximately 13% of the cases of brain tumors and 12% of the cases with salivary gland tumors never had a personal subscription to a cellular phone provider. For the longest duration of subscription (more than 2 years), OR was 1.5 (0.9–2.5).

Two studies examining the association between uveal melanoma (a rare form of cancer of the eye) and exposure to RFR have found no relationship between this cancer and mobile phone use [Johansen et al., 2001; Stang et al., 2001].

Overall, the results indicate that mobile phone use does not increase the risk of brain cancer. Only one group of researchers in Sweden [Hardell et al., 1999, 2000, 2001, 2002a,b, 2003a,b] has reported an association between analog phone use and brain tumors. Their results have found no support in the investigation of other researchers. It is also doubtful whether results for analog phone users can be extrapolated to digital phone users.

IV.C. Summary of Epidemiological Studies

Many epidemiological studies have deficiencies in size, design, analysis, bias, confounding, multiple comparisons, exposure control and assessments, and consistency of results. Based on the above criteria, more weight may be given to those few epidemiological studies with acceptable design and analysis, large number of cases, and minimized potential bias [Milham, 1988; Logorio et al., 1997; Muscat et al., 2000; Inskip et al., 2001] and longer follow-up time [Robinette et al., 1980]. Most of these studies do not show statistically significant association between RFR and cancer. Further studies are underway to evaluate potential carcinogenic effects of exposure from long-term use of mobile phones and other RF sources.

Recently, Elwood [2003] reviewed epidemiological studies of RFR and cancer. He concludes, "The epidemiological results fall short of the strength and consistency of evidence that is required to come to a conclusion that RF emissions are a cause of human cancer. Although the epidemiological evidence in total suggests no increased risk of cancer, the results cannot be unequivocally interpreted in terms of cause and effect. The results are inconsistent, and most studies are limited by lack of detail on actual exposures, short follow-up periods, and the limited ability to deal with other relevant factors. In some studies, there may be substantial biases in the data used."

Where epidemiological evidence for a link between an agent and a disease is weak and the effect is biophysically implausible, laboratory studies become critical for risk evaluation [Foster et al., 1997; Moulder et al., 1999]. Because there are only a few epidemiological studies that examine the health risks associated with exposure to RFR, research at the cellular and animal level is needed to better understand this relationship.

V. CELLULAR AND ANIMAL STUDIES

It is important to distinguish between biological and physiological effects and health effects. A biological effect occurs when exposure to EM fields causes some noticeable or detectable physiological change in a living system. Such an effect may sometimes, but not always, lead to an adverse health effect, which means a physiological change that exceeds normal range for a brief period of time. It occurs when the biological effect is outside the normal range for the body to compensate, and therefore leads to some detrimental health condition. Health effects are often the result of biological effects that accumulate over time and depend on exposure dose. For example, if an effect of EM exposure has been noticed on cultured cells, this does not essentially mean that the exposure will lead to adverse effect for the health of the organism as a whole. In general, the number of cellular and animal studies in the literature is largely due to the great number of cellular processes and systems that may probably be affected by RFR.

V.A. Genetic Toxicology

Genotoxicity does not have a clear cancer endpoint or any other adverse health outcome; however, there is the possibility that genotoxic effects on cells might lead to adverse health effects such as cancer or other diseases. Studies in this regard have been performed at a variety of levels, including damage to deoxyribonucleic (DNA) in vitro or in vivo, damage to chromosomes, induction of sister chromatid exchange (SCE), or induction of phenotypic mutations. A good number of laboratory experiments have been conducted to assess possible genotoxic effects of a broad range of RF frequencies at a variety of levels of biological complexity. Many of the experiments found no evidence for any direct genotoxic or mutagenic effects of RFR at different power densities [Dhahi et al., 1982; Meltz et al., 1987, 1989, 1990; Kerbacher et al., 1990; Malyapa et al., 1997a,b; Antonopoulos et al., 1997; Vijayalaxmi et al., 1997, 2000, 2001a,b; Gos et al., 2000; Maes et al., 2001; Li, et al., 2001; Takahashi et al., 2002; Bisht et al., 2002; McNamee et al., 2002a,b; Zeni et al., 2003]. However, investigations at the University of Washington, Seattle [Lai and Singh, 1995, 1996; Lai et al., 1997] reported an increase in DNA single- and double-stranded breaks in rat brain cells at whole-body SAR levels of 0.6 and 1.2 W/kg, which are lower than the MPE values. Their observations aroused significant interests because of the possible implications with respect to carcinogenesis. Based on these data, two more studies [Malyapa et al., 1997a, 1998] were performed on rat brains using the same SAR levels. However, there was no increased DNA damage. Moreover, Hossmann and Hermann [2003] suggest that the experiments by Lai and Singh used peak power that was much higher than the mean power, which may have accounted for the observed DNA damage.

In a series of studies, Garaj-Vrhovac et al. [1990, 1991, 1992] reported chromosomal damage after exposure of mammalian cells to RFR (7.7 GHz: 0.5, 10, 30 mW/cm^2 for 15, 30, and 60 minutes). Results discussed in these studies suggest that RFR causes changes in the synthesis and the structure of DNA molecules.

Tice et al. [2002], as a part of comprehensive investigation of the potential genotoxicity of RF signals emitted by mobile phones, demonstrated that under extended exposure conditions RFR from mobile phones at an average SAR of at least 5 W/kg are capable of inducing chromosomal damage in human lymphocytes.

Similar findings were reported by d'Ambrosio et al. [2002] while radiating human cells to 1748 MHz at 5 W/kg, and Mashevich et al. [2003] when radiating human lymphocytes to continuous 830 MHz RF energy at SAR in the range 1.6–8.8 W/kg for 72 hours. These results demonstrate that RFR has a genotoxic effect.

In a review, Verschaeve and Maes [1998] concluded, "According to a great majority of articles, RF fields, and mobile telephone frequencies in particular, are not genotoxic: they do not induce genetic effects in vitro and in vivo, at least under nonthermal conditions, and do not seem to be teratogenic (cause birth defects) or to induce cancer."

The Royal Society of Canada Expert Panel Report [Royal Society of Canada, 1999; Krewski et al., 2001] reviewed the subject and concluded, "A large number of laboratory studies of the potential health effects of RF fields have focused on genotoxicity, including studies of tumorigenesis, promotion, progression, altered cell proliferation, and DNA damage. The great majority of these studies have failed to demonstrate genotoxic effects due to exposure to RF fields."

The UK Independent Expert Group on Mobile Phones (IEGMP) [IEGMP, 2000] summarized the situation as follows, "The balance of evidence, from both in vitro and in vivo experiments, indicates that neither acute nor chronic exposure to RF fields increased mutation or chromosomal aberration frequencies when temperatures are maintained within physiological limits. This suggests that RF exposure is unlikely to act as a tumor initiator."

Recently, Meltz [2003] reviewed the in vitro literature pertinent to the issue of the possible induction of toxicity, genotoxicity, and transformation of mammalian cells resulting from RF exposure. The author concludes, "The weight of evidence available indicates that, for a variety of frequencies and modulations with both short and long exposure times, at exposure levels that do not (or in some instances do) heat the biological sample such that there is a measurable increase in temperature, RF exposure does not induce (a) DNA strand breaks, (b) chromosome aberrations, (c) sister chromatid exchanges (SCEs), (d) DNA repair synthesis, (e) phenotypic mutation, or (f) transformation (cancer-like changes)." The author further concludes, "While there is limited experimental evidence that RF exposure induces micronuclei formation, there is abundant evidence that it does not. There is some evidence that RF exposure does not induce DNA excision repair, suggesting the absence of base damage."

Overall, it may be clear at the moment that low levels of exposure to RF fields do not cause genotoxic damage.

V.B. Cell Function

1. Cell Proliferation

Disturbance of normal cell cycle is a possible sign of uncontrolled cell growth, or cancer. Czerska et al. [1992] reported an increased proliferation of cells exposed to 2.45 GHz RFR at SAR of 1 W/kg when the radiation was pulsed. Continuous wave (CW) RFR increased proliferation only when absorbed energy was high enough to induce heating. Other investigators reported increased and decreased cell proliferation rates after applying RFR of various SARs [Cleary et al., 1996; Kwee and Raskmark, 1998; Velizarov et al., 1999; Paulraj and Behari, 2002]. In contrast, d'Ambrosio, et al. [2002] found no significant changes in cell distribution or cell proliferation in cells exposed to 1748 MHz, either CW or phase-only modulated wave Gaussian minimum shift keying (GMSK) for 15 minutes.

2. Intracellular Calcium

Granfield et al. [2001] studied whether exposure to simulated GSM mobile phone signals influences the concentration of calcium or calcium signaling patterns in single cells. The authors estimated the intracellular calcium concentration ($[Ca^{2+}]_i$) in the human lymphocyte cell line, Jurkat, exposed to 915 MHz, 2 W/kg RFR. The results indicated that there is no clear indication that RFR from mobile phones are associated with any changes in calcium levels or calcium signaling in lymphocytes, although an alteration in the frequency of calcium oscillations was noted in activated cells exposed to pulsed wave RFR. However, Guisasola et al. [2002] found that 64

MHz RFR associated with turbo spin echo MRI resulted in a significant increase in $[Ca^{2+}]_i$ in human embryonic lung cells, L-132. Exposure to MRI-related static and gradient fields showed no effect on $[Ca^{2+}]_i$.

3. Ornithine Decarboxylase (ODC)

ODC is an important enzyme for the role it plays in regulating cell growth through synthesis of polyamines necessary for protein and DNA synthesis. ODC is an enzyme activated during carcinogenesis. Increased ODC activity is an indication for cancer. It is believed that low-level modulated RFR can affect intracellular activities of enzymes. Byus et al. [1988] reported evidence of RFR effects on the activity of ODC, ODC messenger RNA levels, and polyamine export in a number of cultured cell lines after exposure to 450 MHz modulated at 16-Hz (1 mW/cm^2) RFR. The effect was noted for certain modulations of the carrier wave illustrating the window effect (an effect that occurs at some combination of exposure conditions, but not at a nearby slightly different set of conditions). Penafiel et al. [1997] reported an increase in ODC activity in L929 cells after irradiation to 835 MHz RFR at SAR of approximately 2.5 W/kg. The results depended upon the type of modulation employed. Amplitude-modulated (AM) frequencies of 16 and 60 Hz produced a transient increase in ODC activity that reached a peak at 8 hours of exposure and returned to control levels after 24 hours of exposure. Paulraj and Behari [2002] also reported increased ODC levels after exposure for 2 hours/day for 35 days to 2.45 GHz RFR at SAR of 0.1 W/kg.

V.C. Hormonal Secretion

An area attracting attention as a likely potential mechanism for RFR intervention in living organisms is a cancer-promoting effect of RFR by altered circadian rhythms of pineal activity and melatonin release. Several investigations examined to what extent hormonal secretion is influenced by RFR. Exposure at ≤0.3 W/kg did not disturb the normal circadian profile of melatonin of the hypothalamo–pituitary–adrenal axis [de Seze et al., 1998, 1999]. However, Stark et al. [1997] conducted a pilot study to investigate the influence of RFR at 3–30 MHz on salivary melatonin concentration in dairy cattle. Two commercial dairy herds at two farms were compared, one located at a distance of 500 m (exposed), the other at a distance of 4 km (unexposed) from a RF transmitter. A chronic melatonin reduction effect seemed unlikely. On the first night of re-exposure after the transmitter had been off for 3 days, the difference in salivary melatonin concentration between the two farms was statistically significant, indicating a two- to sevenfold increase of melatonin concentration in the exposed cows.

V.D. Animal Cancer Experiments

Because RF exposure is not considered to be directly carcinogenic, research should be aimed particularly at its possible promotional and copromotional effects. Different animal studies have been reported whose designs are suitable for describing brain carcinogenesis or brain-tumor-promoting effects of RF energy. It is evident from the literature that few studies [Szmigielski et al., 1982; Repacholi et al., 1997; Trosic et al., 2002] suggest an increased incidence of tumors as a result of exposure to high-level SAR. However, Utteridge et al. [2002] could not replicate the increase in lymphoma either in normal mice or in the same lymphoma-prone mice reported in Repacholi et al. [1997]. Other studies using SARs at modest levels have shown no increase in cancer induction or tumor development rates [Chou et al., 1992; Wu et al., 1994; Repacholi et al., 1997; Stagg et al., 1997; Toler et al., 1997; Imaida et al., 1998; Frei et al., 1998; Adey et al., 1999, 2000; Zook and Simmens, 2001; Mason, et al. 2001; Jauchem et al., 2001; Heikkinen et al., 2001; Bartsch et al., 2002; Vijaylaxmi, 2003; Heikkinen et al., 2003; La Regina et al., 2003].

Recently, Heynick et al. [2003] reviewed studies on cancer and related effects from exposure to EM fields in the nominal frequency range of 3 kHz–300 GHz. They concluded, "The preponderance of published epidemiologic and experimental findings do not support the supposition that in vivo or in vitro exposures to such fields are carcinogenic."

Overall, there is little evidence to suggest that RFR is carcinogenic. However, the few positive results, including those reported by Repacholi et al., 1997, merit further investigation.

V.E. Noncancer Animal Studies

1. Morphological and Physiological Effects

While most experimental studies focus on carcinogenesis, tumor promotion, and mutagenic effects, noncancer effects also need to be considered. RFR may induce other effects, including morphological and physiological changes [Adey, 1981; Adey et al., 1982; Pacini et al., 2002]. According to Adey [1981] and Adey et al. [1982], RF carriers sinusoidally modulated at ELF fields can induce changes to the CNS. However, Tsurita et al. [2000] found no significant morphological changes of the brain in group of rats exposed for 2–4 weeks to a 1439-MHz (2 W/kg) TDMA signal. The exposure period was 2 or 4 weeks.

2. Testicular Function and Development

Bol'shakov et al. [2002] studied the combined effect of 460-MHz RFR and increased (≤40 °C) temperature on Drosophila embryos of definite age. The results of the study indicated that RFR did not produce any notifiable effect on development of the Drosophila. In addition, Dasdag et al. [2003] found no evidence suggesting an adverse effect of mobile phone exposure on measures of testicular function or structure on rats confined in plexiglass cages when mobile phones were placed 0.5 cm under the cages. Mobile phones were activated 20 minutes per day (7 days a week) for 1 month.

3. Cataracts

RFR can induce cataracts if the exposure intensity and the duration are sufficient. Lesions in the cornea, degenerative changes in cells of the iris and retina, and changed visual functions were reported by Kues and Monahan [1992] and Kues et al. [1992] in nonhuman primates after frequent exposures to RFR (CW 2.45 GHz at SAR of 0.26 W/kg) and at 60 GHz and power density of 10 mW/cm^2 [Kues et al., 1999]. However, many studies on the ocular effect of RFR on animals have reported no effects, despite the fact that most studies employed exposure levels greatly in excess of that seen with mobile phones [Carpenter, 1979; Guy et al. 1980; Kamimura, et al., 1994; Lu et al., 2000].

4. Behavioral Effects

Changes in learning behavior occurred after RF exposure at SAR of 1.2 W/kg [D'Andrea et al., 1980] and 2.5 W/kg [De Lorge and Ezell, 1980]. Lai et al. [1994] observed retarded learning of a task in rats exposed to 2.45 GHz. Bornhausen and Scheingraber [2000] found that exposure in utero to the GSM field (900 MHz, 217 Hz pulse-modulated RFR; 17.5 and 75 mW/kg) did not induce any measurable cognitive deficits in exposed Wistar rats during pregnancy. Dubreuil et al. [2002] noted that head-only exposure of rats to 900 MHz pulsed RFR (SAR of 1 or 3.5 W/kg) for 45 minutes had no effect on learning. Also, Yamaguchi et al. [2003] suggest that the exposure to a pulsed 1439 MHz TDMA field at levels about four times stronger than emitted by mobile phones (SAR of 7.5 W/kg or 25 W/kg for

1 hour daily for either 4 days or 4 weeks) does not affect the learning and memory processes in rats when there are no thermal effects.

5. Blood–Brain Barrier (BBB)

RFR-induced breakdown of the BBB have been studied either alone or in combination with magnetic fields. Many authors agree that exposure to RFR increases disruption of the BBB in vivo [Frey et al. 1975; Sutton and Carrol, 1979; Lin and Lin, 1982; Neubauer et al, 1990; Persson et al., 1992, 1997]. However, other studies have not found RFR-induced disruption of the BBB [Ward and Ali, 1981; Ward et al., 1985; Fritz et al, 1997; Tsurita et al., 2000; Finnie et al., 2001, 2002]. Most of the studies conclude that high-intensity RFR is required to alter the permeability of the BBB. Salford et al. [2003] have shown that extremely low doses of GSM radiation can cause brain damage in rats. The authors report nerve damage following a single 2-hour exposure at a SAR of 2 mW/kg. They showed that RFR can impair the BBB, but they add that the chemicals that leak through the BBB probably damage neurons in the cortex, the hippocampus, and the basal ganglia of the brain. The cortex is close to the surface of the skull, while the basal ganglia are much deeper. Recently, D'Andrea et al. [2003a] reviewed the literature on effects of RFR on the BBB. They concluded, "Effects of RF exposure on the BBB have been generally accepted for exposures that are thermalizing. Low level exposures that report alterations of the BBB remain controversial. Exposure to high levels of RF energy can damage the structure and function of the nervous system. Much research has focused on the neurochemistry of the brain and the reported effects of RF exposure. Research with isolated brain tissue has provided new results that do not seem to rely on thermal mechanisms."

VI. CLINICAL STUDIES

VI.A. Perception and Auditory Response

It is believed that when some people are exposed to very low-level RF energy with certain frequency and modulation characteristics, they report hearing sounds [Frey, 1961]. This has been called *auditory phenomena* or *RF hearing*. These sounds—e.g., buzzes, clicks, tones—vary as a function of the modulation. Many studies have been published over the years, especially those conducted by Dr. Chou and his colleagues investigating RF hearing [Chou et al. 1980; Chou and Guy, 1982]. They originally presented the RF-induced auditory phenomena as an example of RF interaction that has been widely accepted as a weak field effect. Although the hypothesis of direct nervous system stimulation was proposed, the alternative is that RF auditory or hearing effect does not occur from an interaction of RFR with the auditory nerves or neurons. Instead, the RF pulse, upon absorption by soft tissues in the head, launches a thermoelastic wave of acoustic pressure that travels by bone conduction to the inner ear and activates the cochlear receptors via the same mechanism for normal hearing.

Kellenyi et al. [1999] found that a 15-minute exposure to GSM phone radiation caused an increase in auditory brainstem response in the exposed side of human subjects. However, Hietanen et al. [2002] indicated that none of the individuals tested with analogue NMT phone (900 MHz) or GSM phones (900 and 1800 MHz) could distinguish real RF exposure from sham exposure.

Recently, Elder and Chou [2003] reviewed the subject and concluded, "The auditory response has been shown to be dependent upon the energy in a single pulse and not on average power density. The weight of evidence of the results of human, animal, and modeling studies supports the thermoelastic expansion theory as the explanation for the RF hearing phenomenon. RF induced sounds involve the perception via bone conduction of thermally generated sound transients, that is, audible sounds are produced by rapid thermal expansion resulting from a calculated temperature rise of only 5×10^{-6} °C in tissue at the threshold level due to absorption of the energy in the RF pulse. The hearing of RF induced sounds at exposure levels many orders of magnitude greater than the hearing threshold is considered to be a biological effect without an accompanying health effect."

VI.B. Thermoregulatory Responses

Thermoregulation, or the maintenance of a fairly steady body temperature even under a variety of external conditions, is important to humans because each body has a preferred temperature at which functioning is optimal. These external conditions can include changes in temperature, vapor pressure, air velocity, exposure to radiation including RFR, and insulation, among other factors that affect the temperature of the skin. Adair et al. [1999] measured thermoregulatory responses of heat production and heat loss in two different groups of seven adult volunteers (males and females) during 45-minute exposure of the whole body to 450 or 2450 MHz CW RFR. At each frequency, two power densities were tested at each of three ambient temperatures (24, 28, and 31 °C) plus temperature controls (no RFR). The normalized peak surface SAR, measured at the location of the subject's center back, was the same for comparable power density at both frequencies—i.e., peak surface SAR = 6.0 and 7.7 W/kg. No change in metabolic heat production occurred under any exposure conditions at either frequency. The magnitude of increase in those skin temperatures under direct irradiation was directly related to frequency, but local sweating rates on back and chest were related more to ambient temperature and SAR. Both efficient sweating and increased local skin blood flow contributed to the regulation of the deep body (esophageal) temperature to within 0.1 °C of the baseline level. At both frequencies, normalized peak SARs in excess of ANSI/IEEE C95.1 guidelines were easily counteracted by normal thermophysiological mechanisms.

In another study, Adair et al. [2001] exposed two different groups of volunteers to 2450 MHz CW (two females, five males) and pulsed wave (PW) (65 s pulse width, 10^4 pps; three females, three males) RFR. They measured thermophysiological responses of heat production and heat loss under a standardized protocol (30-minute baseline, 45-minute RF or sham exposure, 10-minute baseline), conducted in three ambient temperatures (24, 28, and 31 °C). At each temperature, average power density studied were 0, 27, and 35 mW/cm^2 (SAR = 0, 5.94, and 7.7 W/kg). Mean data for each group showed minimal changes in core temperature and metabolic heat production for all test conditions and no reliable differences between CW and PW exposure. Local skin temperatures showed similar trends for CW and PW exposure that were power density dependent; only the skin temperature of the upper back (facing the antenna) showed a reliably greater increase during PW exposure than during CW exposure. Local sweat rate and skin blood flow were both temperature and power density dependent and showed greater variability than other measures between CW and PW exposures; this variability was attributable primarily to the characteristics of the two subject groups. Similar results were obtained by Adair et al. [2003].

Recently, Adair and Black [2003] reviewed the literature concerned with physiological thermoregulatory responses of humans and laboratory animals in the presence of RF fields. They stated, "The conclusion is inescapable that humans demonstrate far superior thermoregulatory ability over other tested organisms during RF exposure at, or even above current human exposure guidelines."

VI.C. Ocular Effects

The cornea and lens are the parts of the eye most exposed to RFR at high levels by their surface location and because heat produced by RFR is more effectively removed from other eye regions by blood circulation. Early investigations of RFR effects on the eye focused on the parameters of power density and duration of exposure required to produce cataracts in the lens of the eye. Hirsch and Parker [1952] reported the first RFR-induced human cataract. However, Cleary and Pasternak [1966] found more subclinical lens changes in a group of 736 microwave workers than in 559 controls, but no cataracts or decrease in visual acuity were noted. The exact conditions under which these changes may occur in humans are a subject of argument [Lin, 1979; Michaelson et al., 1987].

One related modeling study of the human eye by Hirata et al. [2000] showed that 5 mW/cm^2, the MPE value for occupational environments [FCC, 1996], caused a temperature change in the lens <0.3 °C at frequencies from 0.6 to 6 GHz. This small temperature change is overestimated, because the eye model was thermally isolated from the head, and the effect of blood flow was not considered. Therefore, RFR much in excess of currently allowable exposure limits would be required to produce cataracts in human beings, and exposures below the cataractogenic level would be expected to cause other effects in other parts of the eye and face.

Reviews of the literature on RFR-induced cataracts [Tengroth, 1983; Elder, 1984, 2001, 2003] have concluded that clinically significant ocular effects, including cataracts, have not been confirmed in human populations exposed for long periods of time to low-level RFR.

VI.D. Brain Function

The close placement of RFR sources such as mobile phones to the user's head has elevated possibilities of interference with brain activities. While many studies have addressed this issue, they have only investigated the short-term effects of RF exposure. The studies that have considered the effects of RFR on numerous brain functions include slow brain potentials (SP) [Freude et al., 1998, 2000; Krause et al., 2000], cognitive function in humans including shortening of reaction times after exposure to RF signal [Preece et al., 1999; Koivisto et al., 2000; Haarala et al., 2003a,b; Zwamborn et al. 2003], sleep and sleep encephalograms [Mann and Röschke, 1996; Wagner et al., 1998; Borbely et al., 1999], brain function, especially in tasks requiring attention and manipulation of information in working memory [Koivisto et al., 2000a,b, 2001; Smythe and Costall, 2003], electroencephalogram (EEG) activity [Röschke and Mann, 1997; Krause et al., 2000a,b; Hietanen et al., 2000; Huber et al., 2000, 2002, 2003; Croft et al., 2002], brain potential and activity [Reiser et al., 1995; Lebedeva et al., 2000, 2001], and attentional capacity [Lee et al., 2001, 2003; Petrides, 2000, 2001; Edelstyn et al., 2002]. The above studies have demonstrated mixed results. The findings suggest that some aspects of cognitive functions and measures of brain physiology may be affected without offering a uniform view. These include changes in memory tasks, response patterns, normal sleeping EEG patterns, and other brain functional changes. Several studies have demonstrated improved cognitive functions in volunteers exposed to RFR in the frequency range of mobile phones.

Subjective symptoms such as dizziness, disorientation, nausea, headache, and other unpleasant feelings such as a burning sentient or a faint pain might be a direct result of RFR, although such symptoms are very general and may have many other causes. Wilén et al. [2003] made use of information from a previous epidemiological study [Sandstrom et al., 2001] about prevalence of symptoms, calling time per day, and number of calls per day and combined it with measurements of the SAR of the specific mobile phone used by each person included in the above study. Two new exposure parameters have been devised: specific absorption per day (SAD) and specific absorption per call (SAC). The results indicated that SAR values >0.5 W/kg may be an important factor for the prevalence of some of the subjective symptoms, especially in combination with long calling times per day.

Hamblin and Wood [2002] compared the findings of the main studies that have examined the effects of GSM mobile phone RF emissions on human brain activity and sleep variables. They concluded, "Although, in general, outcomes have been inconsistent and comparison between individual studies is difficult, enhanced electroencephalogram alpha-band power has been noted in several of the studies, a phenomenon also observed in some animal studies."

In another review of the literature, Hossmann and Hermann [2003] concluded, "At present, there is little evidence that pulsed or continuous microwave exposure at power and frequencies related to mobile communication could interfere with the functional and structural integrity of the brain. Under experimental conditions, most of the positive results so far could be attributed to thermal effects. Such effects are unlikely to occur during regular use of mobile telephones because the total emitted power is far too low to raise whole body temperature, and because local elevations of brain temperature, if present, would be prevented by the thermostabilizing effect of the circulating blood."

Recently, D'Andrea et al. [2003b] reviewed the literature concerning RF exposure and behavioral and cognitive effects. They conclude, "Reports of change of cognitive function (memory and learning) in humans and laboratory animals are in the scientific literature. Mostly, these are thermally mediated effects, but other low-level effects are not so easily explained by thermal mechanisms. The phenomenon of behavioral disruption by microwave exposure, an operationally defined rate decrease (or rate increase), has served as the basis for human exposure guidelines since the early 1980s and still appears to be a very sensitive RF bioeffect. Nearly all evidence relates this phenomenon to the generation of heat in the tissues and reinforces the conclusion that behavioral changes observed in RF-exposed animals are thermally mediated. Such behavioral alteration has been demonstrated in a variety of animal species and under several different conditions of RF exposure. Thermally based effects can clearly be hazardous to the organism and continue to be the best predictor of hazard for homo sapiens. Nevertheless, similar research with man has not been conducted. Although some studies on human perception of RF exist, these should be expanded to include a variety of RF parameters."

Health Council of the Netherlands [2002] released its report and concluded, "The available scientific data does [*sic*] not indicate an adverse effect on cognitive abilities, even in people who make frequent use of mobile telephones." The Council recommends conducting more research in the Netherlands on the influence of EM fields on cognitive functions.

Despite the absence of serious outcomes, a priority may be given for further research to study the effect of RFR on brain functions. As yet, human studies of cognitive performance and EEG focused on the consequences of short-term exposure. Following a group of new mobile phone users over time could be a good approach to address the issue of long-term exposure. Special attention should be directed toward children, because their developing nervous system is more sensitive to RFR.

VI.E. Cardiovascular Diseases

Jauchem [1997] reviewed cardiovascular changes in humans exposed to RFR. Both acute and long-term effects were investigated. The author reported that most studies showed no acute effect on blood pressure, heart rate, or electrocardiogram (ECG) waveform; others reported subtle effects on the heart rate.

Braune et al. [1998] reported that exposure of human volunteers to RFR of mobile phones (GSM 900-MHz, 2-W, 217-Hz frame repetition rate) increased the sympathetic efferent activity with increases in the resting blood pressure between 5 and 10 mm Hg. However, Braune et al. [2002] repeated their study and summarized that RFR had no effect on the outcomes. They claimed that their 1998 finding of increased blood pressure in mobile phone users was due to an artifact in the design of the original study.

Mann et al. [1998] did not find any effect on the autonomic control of heart rate by applying weak-pulsed RFR emitted by digital mobile phones during sleep in healthy humans, while Huber et al. [2003] found that exposure to 900 MHz at SAR of 1 W/kg affected heart rate variability of healthy young humans.

Recently, Black and Heynick [2003] reviewed the subject and concluded, "Cardiovascular tissue is not directly affected adversely in the absence of significant radiofrequency electromagnetic fields (RFEMF) heating or electric currents. The regulation of blood pressure is not influenced by ultra high frequency (UHF) RFEMF at levels commonly encountered in the use of mobile communication devices."

VI.F. Melatonin

Investigation into RFR effects on melatonin has been conducted in few human studies. Wang [1989] found that workers who were highly exposed to RFR had a dose–response increase in serotonin, indicating a reduction in melatonin. According to Burch et al. [1997], frequent mobile phone use may be associated with reduced daytime melatonin production. Also, Burch et al. [2002] reported that mobile phone use of >25 minutes per day was associated with a drop in melatonin. In contrast, de Seze et al. [1999], Radon et al. [2001], and Bortkiewicz et al. [2002] found no evidence of RFR-related effects on melatonin secretion.

The interpretation of the available data from all types of studies suffers from differences in exposure parameters. Also, there is little evidence that RFR from mobile phones promotes carcinogenesis by depressing melatonin.

VII. DISCUSSION

Reviews of the effects of exposure to RFR have concluded that there are no certainly established, or even firmly suspected, health effects occurring at environmental levels of RFR (Table 4). A significant uncertainty exists in the interpretation of most of the studies. The current evidence from epidemiological, laboratory, and clinical research indicates that environmental RFR does not cause cancer or other diseases. But there is now some evidence that effects on biological functions, including those of the brain, may be induced by RFR at levels comparable to those associated with the use of mobile phones. There is, as yet, no evidence that these biological effects lead to health hazards, but only limited data are currently available.

Two large reviews [Verschaeve and Maes, 1998; Brusick et al., 1998] concluded that RFR below the existing MPE values is not directly genotoxic. In the review of cancer studies, the IEGMP [IEGMP, 2000] of the UK concluded, "Some individual experimental studies have suggested that RFR can initiate tumor formation, enhance the effects of known carcinogens or promote the growth of transplanted tumors. However, in some of these studies, the intensity was high enough to produce thermal effects. The balance of evidence, both in vitro [*sic*] and in vivo experiments, indicates that neither acute nor chronic exposure to RFR increases mutation or chromosomal aberration frequencies when temperatures are maintained within physiological limits."

The Swedish Radiation Protection Authority supports the commonly accepted view that RF energy, at least under levels of power emitted by mobile phones, is not genotoxic and cannot directly damage DNA, and are thus unlikely to be initiators. Hence the risk of cancer from a thermal or nonthermal mechanism would be one that, if anything, promotes tumor growth. Nevertheless, there is no convincing evidence from animal experiments or epidemiologic research that RF signals can promote tumor growth or induce genetic effects [Boice and McLaughlin, 2002]. However, there might be effects under extended exposure conditions or at high-level SARs.

It is important to note that modulated or pulsed RFR seems to be more effective in producing an effect. It can also elicit a different effect, especially on brain

TABLE 4. Summary of Recent Reviews of Literature on Health Risk of RFR

Reference	Evaluation
Brusick et al., 1998	There is insufficient evidence to indicate that RF signals are directly mutagenic. The majority of published RF studies reporting a positive genotoxic effect were flawed because of poor biological design, inadequate dosimetry, and/or an inability to eliminate potential thermal effects.
CDRH, 1999	The available science does not allow us to conclude that mobile phones are absolutely safe or that they are unsafe. However, the available scientific evidence does not demonstrate any adverse health effects associated with the use of mobile phones.
Moulder et al., 1999	The epidemiological evidence for an association between RF radiation and cancer is found to be weak and inconsistent. The laboratory studies generally do not suggest that cell phone RF radiation has genotoxic or epigenetic activity, and a cell phone RF radiation/cancer connection is found to be physically implausible.
COMAR, 2000	Engineering data indicate that local SARs produced by handheld, transportable, and mobile transceivers and cellular telephones normally do not exceed FCC and other safety limits. Present scientific evidence, as reviewed by standards-setting organizations and other expert groups, does not demonstrate health or safety risks from cellular and other communications transceivers. A potential exists for interference between handheld units and some medical devices that may be located in close proximity to them (within a few centimeters).
Royal Society of Canada, 1999; Krewski et al., 2001	Because cellular telephones and similar devices have been in use for a relatively short period of time, further observation may be required to fully examine potential health effects from long-term exposure to RF fields. Based on a comprehensive review of the scientific literature, an expert panel of the Royal Society of Canada concluded that there is no clear evidence of an association between RFR and adverse health effects at this time. However, the panel noted a number of biological effects not known to be of clinical significance that require clarification.
IEGMP, 2000	The balance of evidence indicates that there is no general risk to the health of people living near base stations on the basis that exposures are expected to be small fractions of guidelines. Children may be more vulnerable to health effects from use of mobile phones because of their developing nervous systems, the greater absorption of energy in the tissue of their heads, and a longer lifetime of exposure. We conclude therefore that it is not possible at present to say that exposure to RF radiation, even at levels below national guidelines, is totally without potential adverse health effects and that the gaps in knowledge are sufficient to justify a precautionary approach.
American Cancer Society, 2001	There is now considerable epidemiological evidence that shows no consistent association between cellular phone use and brain cancer. The lack of ionizing radiation and the low energy level emitted from cell phones and absorbed by human tissues makes it unlikely that these devices cause cancer.

Reference	Evaluation
Zmirou et al., 2001	Scientific data indicates, with comparative certainty, that as a result of exposure from RF from a mobile phone, a variety of biological effects occur (e.g., electroencephalogram profile, reaction time) at energy levels that do not cause any local increase in temperature. However, in the current state of knowledge of these nonthermal effects, it is not yet possible to determine whether they represent a health hazard. The report further states that if future research were to validate this hypothesis—i.e., demonstrate the existence of health hazards—the risk, at an individual level, would probably be very low. Indeed, it is reassuring to note that it has not yet been demonstrated, in spite of the considerable amount of work done over the past several years. However, if mobile phone radiofrequency fields were hazardous, the very high number of mobile telephone users could mean that, even if the individual risk were very low, the impact on public health could be considerable.
European Commission's Scientific Committee, 2001	The additional information that has become available on carcinogenic and other nonthermal effects of radiofrequency and microwave radiation frequencies in recent years does not justify a revision of exposure limits set by the Commission on the basis of the conclusions of the 1998 opinion of the Steering Scientific Committee. In particular, in humans, no evidence of carcinogenicity in either children or adults has resulted from epidemiological studies.
British Medical Association, 2001	The most recently published reviews of the literature have concluded that while there are small physiological effects within the existing guidelines, there are no definite adverse health effects from mobile phones or their base stations. However, all the main professional organizations have called for more research to be conducted, because the possibility that radiofrequency radiation may cause adverse effects cannot be ruled out on the currently available data. Clearly, there are large gaps in the knowledge that need to be addressed.
Frumkin et al., 2001	Because cellular phones are a relatively new technology, we do not yet have long-term follow-up on their possible biological effects. However, the lack of ionizing radiation and the low energy level emitted from cell phones and absorbed by human tissues make it unlikely that these devices cause cancer.
Health Council of the Netherlands, 2002	The electromagnetic field of a mobile telephone does not constitute a health hazard, according to the present state of scientific knowledge. Therefore, there are no reasons for a revision of the exposure limits.
IEE, 2002	The IEE Policy Advisory Group on the Biological Effects of Low Level Electromagnetic Fields has concluded that there is still no convincing scientific evidence that shows harmful effects of low-level electromagnetic fields on humans. This conclusion is the same as that reached in its previous position statement, the last being in May 2000, and has not been changed by the peer-reviewed literature of the past two years.

continues

TABLE 4. *(continued)*

Reference	Evaluation
Boice and McLaughlin, 2002: Swedish Radiation Protection Authority	Overall, the epidemiologic and laboratory studies to date have ruled out with a reasonable degree of certainty that cellular telephones cause cancer, at least for durations of use up to 5 years.
Hamblin and Wood, 2002	Although in general outcomes have been inconsistent, and comparison between individual studies is difficult, enhanced electroencephalogram alpha-band power has been noted in several of the studies, a phenomenon also observed in some animal studies. Significant cognitive effects have been reported using both modulated and unmodulated radiofrequency carriers. The possibility of putative effects being due to extremely low frequency demodulation is therefore unlikely. There are no obvious associations between the site of exposure and regions of the brain from which effects are reported or implied.
Lin, 2002	The persistent public concern about the biological effects and safety of microwave exposure from wireless base stations can be traced, in part, to the public's desire to protect itself from unnecessary exposure to potentially harmful radiation, including RF and microwaves associated with cellular mobile telecommunication operations. This concern is posing new questions about the adequacy of the existing knowledge of biological effects of RF and microwave electromagnetic fields and on the adequacy of the protection afforded the public from the harmful effects of these fields. Existing guidelines and standards were developed primarily from a scientific database derived using continuous-wave (CW) exposures. While some studies have reported biological effects specific to the signal forms and modulations commonly used by wireless mobile telecommunications, a majority of recent studies using these signal forms and modulations did not show any effect. However, given the confined scope and extent of recent studies, a wider range of investigations would be propitious in elucidating the safety of wireless base stations.
AMTA, 2003 : Australian Mobile Telecommunications Association	The Australian Government's response to the Senate inquiry into electromagnetic radiation should reassure the Australian public about the safety of mobile phone technology. The Inquiry found no substantiated scientific evidence of health effects from mobile phones and their base stations that comply with strict safety guidelines, which has now been reiterated by the Government.

function, when compared with CW RFR of the same characteristics. Many studies supporting this fact have been summarized throughout this article. Juutilainen and de Seze [1998] reviewed this matter extensively.

Experimental investigations of weak ELF field (including RFR–ELF associated with mobile phones) effects on human physiology have yielded some evidence of an effect in a number of different areas, such as heart rate variability, sleep disturbance, and melatonin suppression [NIEHS, 1998; Cook et al., 2002]. In general, there have been inconsistencies in results between experiments because of various experimental protocols and exposure characteristics. Adair [2003] reviewed this subject, and by using biophysical criteria, demonstrated that it is unlikely that low-intensity fields can generate significant physiological consequences.

An important area of research that needs further investigation is health risk associated with children's use of mobile phones. Following recommendation from the IEGMP [IEGMP, 2000], the UK government recently published a brochure recommending that the children up to the age of about 16 years should minimize the use of mobile phones. The IEGMP notes that the head and nervous system continue to develop until about 16 years of age. The density of synapses reaches adult level around puberty, and skull thickness and brain size reach adult levels around ages 14–15 years. Because of higher tissue conductivity (higher water content and ion concentrations), children may absorb more energy from a given mobile phone than do adults. Health Council of the Netherlands [2002] advocates against the IEGRP recommendation. The Council feels there is no reason to recommend that children should restrict the use of mobile phones as much as possible. In this regard, we feel that children's use of mobile phones is a critical area of research that needs further dosimetrical and laboratory investigations.

VIII. CONCLUSION AND RESEARCH NEEDS

The potential for exposure to RFR resulting in adverse health outcomes has been the subject of intensive investigation. Current studies indicate no clear evidence of an association between RFR and increased health risk. Many of the early studies are subject to methodological deficiencies, limiting their utility in assessing potential RFR health risks. However, the possible effects of long-term exposure to RFR are unclear and require clarification.

At this point, it appears that RFR may pose a human health risk only at moderately high levels of exposure. Most environmental exposures to RFR, such as those from mobile phones, are relatively low, although measurable. The detection of biological responses at such low exposure levels will require either large-scale population-based studies with the sensitivity to identify small risks, should they exist, or sophisticated assays employing sensitive biomarkers of exposure and biological effects.

Additional research on RFR is required to narrowly address the following areas of uncertainty: (1) biophysical interaction mechanisms to explain observed in vitro and in vivo effects at field levels to which the public is exposed; (2) enhanced dosimetry techniques to obtain better measurements of RFR exposure; (3) in vitro and in vivo research to obtain reproducible results on previously reported genetic and carcinogenic effects; (4) experimental studies to clarify possible effects related to circulating melatonin, sleep disruption, heart rate, learning, and memory; (5) clinical studies focusing on cognitive, behavioral, and physiological effects on the CNS (especially in children, whose nervous systems remain under development), and (6) epidemiological studies to investigate the effects of long-term exposure to RFR and cancer risk (particularly cancers of the head and neck area in relation to RF exposures from mobile phones). Collectively, this information will strengthen the scientific basis on which a more complete assessment of RFR health risks can be made. In addition, efforts are needed to better understand public perception of RFR risks, which may assist in setting up risk communication strategies that lead to the management of health risks [see Part III of this three-part article, due in the next issue of this journal].

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