7

Exposures to ELF-EMF in Everyday Environments

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CONTENTS

Introduction

A crucial step in epidemiology involves understanding the exposures that may affect human health. This chapter covers the basic elements that determine exposures to electric and magnetic fields (EMFs) at extremely low frequencies (ELFs ≡ >0–3000 Hz) in everyday environments, particularly electric utilities, residences, schools, offices, transportation, and manufacturing. The chapter starts with an overview of basic concepts. For each environment, important sources of ELF-EMFs are described, followed by a brief survey of exposure measurements.

Basic ELF-EMF Concepts

The objectives of this section are to introduce the terminology, notation, and physical concepts used in the assessment of ELF-EMF exposures. The focus is on the physical characteristics of EMF that have been hypothesized to affect human health. Important terms are denoted by italics. Additional details on these terms can usually be found in *Wikipedia*®, whereas instructive illustrations can be found by searching with *Google*® *Images*.

Definitions and Units

From an epidemiologic perspective, electric fields (EFs) and magnetic fields (MFs) are *force fields* that electricity exerts on charged particles in the body, such as electrons, ions, and polarized molecules. In everyday environments, an EF (ε) is determined by an electric circuit's *voltage* and is measured in volts per meter (V/m). An MF is determined by the circuit's *current*. In the ELF range, MF exposures are measured as the *magnetic flux density* (B) in units of microtesla (μT). (In the United States, the MF unit is often reported in milligauss (mG), whose conversion factor is 1 μT = 10 mG.) More rigorous definitions of EMF are given in electromagnetism textbooks such as Jackson (1999) and Griffiths (2013).

The *electromagnetic spectrum* divides EMF into categories, such as ultraviolet (UV) and radio frequency (RF) radiation, as a function of *frequency* (f) measured in hertz (Hz = cycles per second). The spectrum ranges from static EMF at 0 Hz to gamma rays with frequencies above 10^{19} Hz. Frequency is a key indicator of EMF toxicity because it determines the severity of molecular changes (ionization, photochemistry, heating) that result from exposure to *electromagnetic radiation*.

In everyday environments, ELF-EMFs are unsynchronized fields (known technically as *near fields*) rather than radiation, yet their frequency can still determine their effects on the body, especially through *magnetic induction.* This relationship between frequency and magnetic induction is so important to ELF-EMF health effects that its mathematical basis should be understood by all practitioners. According to *Faraday's law,* a time-varying MF $B(t)$ induces EFs inside the body whose strength is proportional to the derivative dB/dt. For MFs emitted by *alternating current* (AC) electricity, $B(t)$ has the same sinusoidal time dependence as the AC current with f = 50 or 60 Hz. Therefore, the induced electric field $E_{in}(t)$ is related to frequency by

$$E_{\text{in}}(t) \propto \frac{d}{dt} B_{\text{pk}} \sin(2\pi ft) \propto 2\pi f B_{\text{pk}} \cos(2\pi ft) \tag{7.1}$$

In other words, both the MFs magnitude B_{pk} and the frequency f determine the induced field. Due to this frequency dependence of magnetic induction, the ELF frequency band has served as a useful indicator of toxicity in health effects studies.

Of the many definitions for *extremely low frequencies* (SCENIHR 1997; WHO 2007; ITU 2008), this chapter uses ELF ≡ >0–3000 Hz as the range best representing time-varying EMF exposures in everyday environments where AC electricity is the primary source. The 3000 Hz upper limit originated in the International Telecommunications Union's system for radio bands (ITU 2008) and is currently used with the ELF band for atmospheric radio waves (Barr et al. 2000). The criterion for the lower end of the ELF band is that an MF exposure varies with time ($f > 0$ Hz) so that the *magnetic induction* mechanism can operate. This leads to the consideration of the time-varying exposures from a person's motion in the earth's MF, fields that are called *motion gradient magnetic fields* (MG-MFs).

Occasionally, sources of ELF-EMF also emit fields in other frequency bands: static MFs (0 Hz), intermediate frequencies (3000 Hz–10 MHz), and radio frequencies (10 MHz–300 GHz). In such cases, this chapter mentions a source's other frequencies but focuses on its ELF emissions.

Summary of Definitions and Units

- The EF is determined by the voltage of electric circuits and is measured in volts per meter (V/m).
- An ELF-MF is determined by the circuit's current and is measured as the magnetic flux density (B) in units of microtesla (μT).
- The ELF band encompasses time-varying EMF in everyday environments where AC electricity is the primary source, and magnetic induction is an important biophysical mechanism.

EMF Physical Characteristics

EMFs are vectors, denoted **E** and **B**, with a magnitude and a direction in space. **E**'s direction at a given location is determined by the voltage's sign (+ or –), and the relative positions of the wires and nearby objects, particularly the earth. Likewise, the current's direction in a wire along with its geometry determines **B**'s direction (Figure 7.1). *Direct currents* (DCs) therefore generate a static MF $\mathbf{B}_0$ (Figure 7.1a), whereas AC currents generate an oscillating field **B**(t) with the same frequency as the current (Figure 7.1c).

In everyday environments, a person is surrounded by many wires whose EMFs add vectorially to give the person's net EMF exposure. A simple example is an electric line with only "hot" and neutral return wires and equal currents running in opposite directions, therefore generating opposing MF vectors (Figure 7.1b and 7.1c). When two insulated wires in a cable are touching, their MF vectors effectively cancel each other. With separated electric lines, the cancellation is incomplete, leaving a net MF > 0 (Figure 7.1b–7.1d).

As Figure 7.1 shows, the *polarization* or shape traced by the MF vector depends on the currents' *phases* or timing of their peaks. Single-phase currents where the two wires have

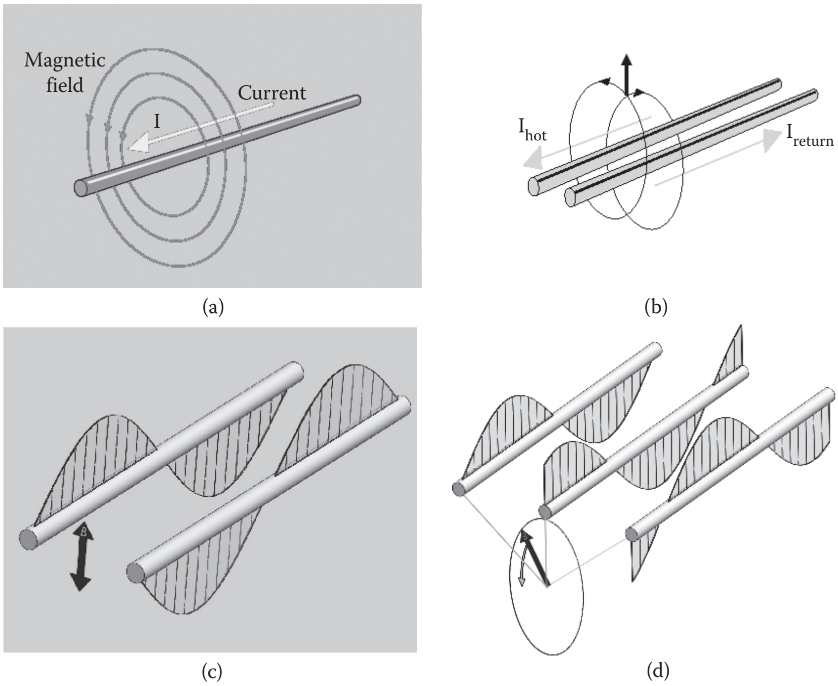


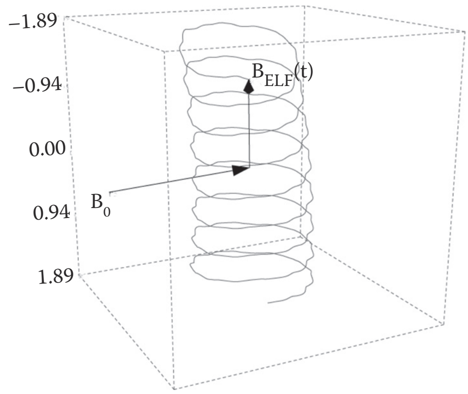
FIGURE 7.1
Net MFs from electric lines. (a) Single wire with DC electricity. (b) DC circuit. (c) Single-phase AC circuit. (d) Three-phase AC power line. (Original graphic by Joseph DeCapite [NIOSH]).

the same phase produce *linearly polarized* MFs (Figure 7.1c). *Elliptically polarized* fields are generated by the three-phase currents used in electric transmission and distribution lines (Figure 7.1d) as well as powerful electric motors and other industrial sources. Elliptical polarization can also arise from the sum of the fields from multiple single-phase sources with different *power factors* (the phase difference between the current and voltage). Similar relationships apply to the EF's polarization and the phases of its source voltages (Deno and Silva 1998).

This EMF cancellation between multiple electric wires also makes their net vector magnitude fall off more rapidly with the distance r from the line (Kaune and Zaffanella 1992). With a single wire (Figure 7.1a), the MF magnitude is proportional to $1/r$, a distance dependence that also applies to a multiwire power line with a non-zero *net current* (sum of the currents from all lines factoring in their phases) (Kaune and Zaffanella 1992). When the net current of a power line is zero (Figure 7.1c and 7.1d), the MF falls off as $1/r^2$. With the coils of wire found in electric motors and *solenoids*, the distance dependence is $1/r^3$.

These distance relationships between ELF-MFs and their source continue within our bodies and most other matter, except for ferromagnetic metals such as iron and nickel. Iron and steel strongly perturb MF in ways that either decrease or increase exposures, depending on the geometry.

In contrast, all matter interacts strongly with EFs, and in the everyday environment, usually decreases exposures. An extreme example is the *Faraday cage*, a conductive metal cage that has zero EF inside. Because the ionized water within our body makes it somewhat conductive, the same physical principles reduce the EF inside a human body to roughly 10^{-6} (one millionth) of its exterior magnitude (Kaune et al. 1990). This interaction with matter greatly



Magnetic Field Magnitudes (µT):	Freq. (Hz)	Mag. (µT)	Axis Ratio (%)
Static (B_0): 33.73	60	0.819	77
ELF+Gradient: 1.279	180	0.050	36
Fullband (ave.): 33.746	540	0.020	11

FIGURE 7.2
Trace of an MF vector $\mathbf{B}_0 + \mathbf{B}_{ELF}(t)$ measured on an electric line worker working on a distribution line from a bucket truck. (Bowman J. D. et al., Electric utility worker exposures to biologically based metrics for ELF and static magnetic fields measured by the Multiwave System III. In press.) In this graph, $\mathbf{B}_{ELF}(t)$ includes the MG, power–frequency, and harmonic components in Equation 7.1. Note: The $\mathbf{B}_0$ vector is actually 33.73 µT, but is truncated at the edge of the ±1.89 µT cube to get a better view of the trace. To improve the perspective, $\mathbf{B}_0$ is also rotated from its actual 67° downward inclination. (Computer generated plot by Joseph Bowman [NIOSH]).

complicates an EF's distance relationship to its source. The EF between two metal plates is unchanged between the high-voltage plate and the grounded plate where $V = 0$ volts. The field's strength is $E = V/d$, where d is the distance (meters) between the plates. Applying this relationship to the EF underneath a power line, the field strength decreases inversely with the height of the line but is approximately constant between the line and the ground.

More complicated are the MFs encountered in everyday environments due to the many sources in the environment. Figure 7.2 shows the trace of the MF vector measured with a 0–3000 Hz probe worn by a California electric line worker working on a distribution line from a bucket truck (Bowman et al. 2014). This complicated trace results from four sources in the worker's environment. First, a static MF with magnitude $B_0 = 33.7$ µT came from the earth's geomagnetic field perturbed by steel in the environment. Second is a 60 Hz MF component from the three-phase AC electricity of the line that gives the trace its periodic elliptical shape. Third are the 180- and 540 Hz *harmonic* frequencies (multiples of 60 Hz) that come from rectifiers and other nonlinear electronics plugged into the distribution system and that create the periodic wiggles in the trace. Finally, the periodic spiral is due to the worker's movement through gradients in the earth's MF near steel objects. With this typical example of ELF-MFs in everyday environments, the instantaneous vector can be represented by the sum of its frequency components:

$$\boldsymbol{B}(t) = \boldsymbol{B}_0 + \boldsymbol{B}_{motion\,gradient}(t) + \boldsymbol{B}_{f_{power}}(t) + \sum_{n>1} \boldsymbol{B}_{nf_{power}}(t) \tag{7.2}$$

where f_{power} is the power frequency (60 Hz in North America and Brazil, 50 Hz in the rest of the world; 400 Hz on airliners; and several other frequencies on trains). The harmonic index n is usually limited to 3 and 5 due to the dynamics of complex AC circuits, but it can have a spectrum with other values near nonlinear electric equipment, a common occurrence in manufacturing plants (Bowman and Methner 2001).

Summary of EMF Physical Characteristics

- An ELF-EMF is a vector that varies with time, space, and (generally) frequency.
- The degree of cancellation among ELF-MFs from electric circuits determines how rapidly the field decreases with distance, ranging from $1/r$ for an unbalanced current to $1/r^3$ for wire coils.
- MFs are largely unchanged by our bodies and most matter, whereas EFs interact strongly with matter, thereby shielding people from exposures in most cases.
- The time-varying components of ELF-MFs are generally the power frequency, its harmonics, and the MG field.

EMF Exposure Metrics

An exposure metric is typically a single number that summarizes a person's exposure to EFs, MFs, or both. Exposure metrics are essential components of occupational and environmental health research and practice, both for epidemiologic analyses and setting exposure limits. Examples for other agents are the effective irradiance in W/m^2 for UV radiation, the A-weighted sound pressure level in dBA (A-weighted decibels) for noise, or the respirable fraction in mg/m^3 for dusts that cause pneumoconiosis (ACGIH 2001).

To convert a person's exposures to time-dependent EMF vectors as in Figure 7.2 into a single number, an exposure metric identifies and combines frequency and spatial and temporal characteristics of the field (Bowman et al. 1998). Over short time scales (<1 s), a common metric is the root mean square (RMS):

$$\mathrm{RMS}\left[S(t)\right] = \sqrt{\frac{1}{T}\int_{t}^{t+T} S(t')^2\,dt'} \equiv x_t \tag{7.3}$$

where T is an averaging time, t is the measurement's start time, and $S(t)$ is a scalar function of an EMF vector. The simplest scalar function for an EMF vector is its magnitude:

$$\left|\mathbf{B}(t)\right| = \sqrt{B_x(t)^2 + B_y(t)^2 + B_z(t)^2} \tag{7.4}$$

where measurement probe(s) are aligned along the x, y, and z axes. Combining Equations 7.2 and 7.3 gives the *rms vector magnitude*:

$$B_t = \mathrm{RMS}\left[\left|\mathbf{B}(t)\right|\right] = \sqrt{B_{xt}^2 + B_{yt}^2 + B_{zt}^2} \tag{7.5}$$

A useful alternative metric is the peak vector magnitude $B_{pk,t} = \mathrm{Max}\ |\mathbf{B}(t)|$. For sinusoidal fields such as in Figure 7.1c and 7.1d, the peak and rms fields are related simply by $B_{pk,t} = \sqrt{2}B_t$ (Blume 2007, p. 233) although the relationship is more complicated for most environmental fields (Figure 7.2). In addition, an EMF meter usually applies a frequency *filter* to the total field (Equation 7.2) and gives metrics such as the static field magnitude $B_{0,t} = \sqrt{B_{0x,t}^2 + B_{0y,t}^2 + B_{0z,t}^2}$ or the peak ELF magnitude over one period $B_{pk,\mathrm{ELF},t} = \mathrm{Max}[|\mathbf{B}_{\mathrm{ELF}}(t')|$ where t' ranges over a single cycle.

An important variant of these exposure metrics is the *resultant,* which was developed to test the Wertheimer–Leeper (WL) hypothesis that residential MF from AC power lines is associated with increased risks of childhood cancers (Wertheimer and Leeper 1979). In the first two studies to test the WL hypothesis with measurements (Savitz et al. 1988; London et al. 1991), ELF-MF exposures in residences were assessed by spot measurements with a single-axis induction coil probe. To assess the rms vector magnitude (Equation 7.5) at a location within the home, three measurements were taken with the probe aligned in the x, y, and z directions, and the rms components were then combined with the resultant formula:

$$B_{r,t} \equiv \sqrt{B_{x,t}^2 + B_{x,t+\delta}^2 + B_{z,t+2\delta}^2} \tag{7.6}$$

where δ is the time between component measurements. Note that the resultant measures the three orthogonal components sequentially, whereas the rms vector magnitude (Equation 7.4) measures them simultaneously. These spot measurement protocols placed the induction coil probe on a stand that both aligned the probe in the three orthogonal directions and kept it stationary. This stationary probe holder eliminated the MG field (Equation 7.2) from the measurements, so these studies only assessed MF exposures from AC electricity, according to the WL hypothesis.

Because spot measurements are severely limited in assessing exposures to the highly variable MFs found in most homes and workplaces, the Electric Power Research Institute (EPRI) undertook an instrumentation development program to develop a personal meter with data-logging capability so that ELF-MF exposures could be measured for at least 24 hr in epidemiologic studies of the WL hypothesis (Bracken et al. 1993). This effort ultimately resulted in the EMDEX family of ELF-MF personal and spot measurement meters (Enertech Consultants, Campbell, CA) that were used in the overwhelming majority of epidemiologic studies described in Chapters 9–11.

The EMDEX meters measure the MF resultant with a three-axis probe at sampling rates ranging from 1.5 to 10 s over periods up to 24 hr. Like the spot measurement method described above, EMDEXs measure the rms components from the three probes sequentially, where the time δ between measurements increases with the meter's *sampling interval* (between 1.5 s and ~6 min, depending on the model and the meter's programming [Enertech Consultants 1993]). To eliminate both the MG-MF and higher frequencies, the EMDEXs have a *band-pass filter* with a lower bound at 40 Hz and an upper bound that depends on the model (800 Hz for the EMDEX II and 1000 Hz for the EMDEX Lite). The EMDEX's primary output is labeled the *broadband resultant* to distinguish it from measurements with the *harmonic mode*, whose filter has a 100 Hz lower bound (Enertech Consultants 1993).

Because ELF-MFs are not perturbed by the body, measurements of the ELF resultant with an EMDEX meter worn on the subject's body (typically the waist) give a reasonable assessment of personal MF exposures to the rms vector magnitude from AC electricity. The greatest inaccuracy is an MF whose vector trace varies in a nonperiodic manner over the sampling interval 2δ. (The trace in Figure 7.2 is nonperiodic due to the MG, but similar variations can result from rapid changes in the source current or the person's distance from the source.) When the MF trace diverges rapidly from periodicity, the resultant's errors relative to the rms vector magnitude have been as much as 3000% (Bowman and Methner 2001; McDevitt et al. 2002).

Exposure metrics for EFs are more difficult to define and measure because they are strongly perturbed by all objects including our bodies and, therefore, vary with body location and posture (Chartier et al. 1985). For health studies, most surveys of personal EF exposures have used the Positron monitor that only measures the rms EF component perpendicular to the meter's 8 × 14.3 cm case, an imperfect surrogate metric (Heroux 1991). The resulting uncertainty about the EF's impact on the body means that both area and personal measurements should be treated as semiquantitative exposure indicators.

In this chapter, the principal short-term exposure metrics are the rms component perpendicular to the body for the EFs and the ELF resultant for MFs because so much of these data were collected with the convenient Positron and EMDEX monitors in surveillance and epidemiologic studies.

In chronic disease studies, the EMDEX and Positron monitors collect thousands of measurements in their datalogger, so *long-term metrics* for time scales greater than 1 sec are needed to summarize exposure for epidemiologic analysis or exposure guidelines. Although a score of long-term metrics have been used (Morgan and Nair 1992; Zaffanella 1998; Yost 1999; Bowman et al. 2010), the metric used most often in studies of cancers and other chronic diseases has been the time-weighted average (TWA):

$$\begin{aligned}\mathrm{TWA}[S_t] &= \sum_{i=1}^{N} S_{t_i}\ \ t_i \Big/ \sum_{i=1}^{N}\ \ t_i \\ &= \frac{1}{N}\sum_{i=1}^{N} S_{t_i} \quad \text{if} \quad t_i \text{ is constant.}\end{aligned} \tag{7.7}$$

where Δt_i is the time between two samples and S_t is a short-term scalar metric measured at time t.

A mechanistic rationale for using the TWA[S_t] in health studies is that its integral over the response time (i.e., the cumulative exposure) is proportional to the damage to the target organ if all intermediate biologic processes are linear functions of the metric S (Rappaport and Kupper 2008). For acute adverse effects such as electrostimulation with a millisecond response time, a useful long-term metric is the maximum of the short-term metric over the sampling period Max[S_t].

Epidemiologists, however, should be aware that scores of other short-term EMF exposure metrics have been defined (Bowman et al. 1998, 2010), such as the fullband magnitude (the rms vector magnitude of Equation 7.1) and the axial ratio (a measure of polarization) displayed in Figure 7.2. For EMF health studies, metrics derived from biophysical mechanisms should be better predictors of disease risks, as they are for other physical and chemical agents (Smith and Kriebel 2010). For example, the electrostimulation of voltage-gated ion channels in neurons by magnetic induction has been shown to cause adverse neurologic effects (Reilly 1998). Based on magnetic induction models (Equation 7.1), one of the safety guidelines for ELF-MF (IEEE 2002) recommends two short-term metrics as improvements on the rms vector magnitude: the peak vector magnitude of the MF's time derivative, $|\partial \boldsymbol{B}(t)/\partial t|_{pk}$, and the peak internal EF magnitude induced at the target organ, $|E|_{in,\,pk}$. Similarly, a study of magnetic navigation in birds and other animals (Vanderstraeten and Vorst 2005) suggests that the rms angle of oscillation of $\mathbf{B}(t)$ (Equation 7.2) relative to the static MF vector $\boldsymbol{B}_0$ as a short-term metric sensitive to the free radical and magnetosome mechanisms that are part of animal magnetoreception (Mouritsen and Ritz 2005).

Combining all the long-term and short-term metrics that have been proposed in the ELF literature results in a daunting number of possibilities—294 combinations in one compilation (Bowman et al. 2010). Ideally, health studies can sharply reduce the number of metrics to be evaluated by focusing on those derived from biologic mechanisms hypothesized as causes of the disease under investigation. Chapter 17 discusses some approaches for selecting EMF metrics (or "effect functions") for epidemiologic studies from the consideration of laboratory findings. The identification of the best exposure metric for health effects such as cancer and neurodegenerative diseases remains a major challenge for ELF-EMF research.

Summary of EMF Exposure Metrics

- An exposure metric is a single number that summarizes a person's exposure to an agent for either an epidemiologic analysis or an exposure limit.
- An exposure metric for ELF-EMF selects and combines the field's frequency, spatial, short-term (<1 s), and long-term characteristics into a single number.
- A convenient short-term metric for ELF-MF is the rms vector magnitude that is commonly measured by EMDEX instruments with an approximation called the "broadband resultant."
- All ELF exposure metrics derived from viable biophysical disease mechanisms involve other field characteristics besides the rms vector magnitude of the ELF-MF, yet most epidemiologic studies have measured exposures with the broadband resultant.

Population Statistics

Finally, EMF magnitudes are summarized in the rest of this chapter by tables of *population statistics* for the ELF resultant from sources and environments in everyday environments. As discussed in the survey paper (Kheifets et al. 2013), this choice of the ELF resultant for MF and the perpendicular component of the EF is motivated by the immense amount of such data available from ELF epidemiologic and surveillance studies, despite its questionable biologic significance. The tables use the geometric mean (GM) as its statistic for the central tendency of exposures in everyday environments because ELF-EMF exposures follow other occupational and environmental agents in belonging to log-normal distributions across a population (Rappaport and Kupper 2008). For between-person variability, the geometric standard deviation (GSD) is often used in exposure assessments (Rappaport and Kupper 2008), but this chapter reports instead the 95th percentile (P95) because it has the same units as the GM, facilitating comparisons. By assuming a log-normal distribution, the two variability statistics are related by $P95 = GM\ GSD^{z_{0.95}}$ where the standard normal quantile $z_{0.95} = 1.64$.

Note that the GM and P95 are occasionally used as long-term EMF metrics (e.g., Zaffanella 1998), but such statistically based exposure metrics should not be confused with population statistics. Likewise, the long-term metric TWA is sometimes called the arithmetic mean (AM), so to avoid confusion, this chapter uses the term AM only for the population statistics.

Summary of Population Statistics

- Because ELF-EMFs in most environments are distributed log-normally, the central tendency of a population's exposure is given as the GM and its exposure variability by the GSD or the 95th percentile (P95).
- To avoid confusion, the term "arithmetic mean" (AM) should only be used for population statistics, whereas TWA should be used for the arithmetic mean over time, a long-term exposure metric.

Electric Power Systems

Having covered the basic principles needed for exposure assessment, the remainder of this chapter surveys ELF-EMF sources and exposures encountered in the different environments of everyday environments: the electric power system, residences, schools, offices, manufacturing, other workplaces, and the MG fields. The section for each environment first discusses the main sources and then summarizes data on personal exposures. Due to the uncertain relevance to health effects of the ELF-MF resultant and the EF metric measured across these environments, this survey emphasizes determinants of exposure rather than numbers. Nonetheless, Table 7.1 gives a few benchmarks on ELF-EMF health effects to help put the exposures from these environments into perspective.

Modern society is powered by an intricate system of electric generation, transmission, and distribution lines ending with the electrical wiring in homes and workplaces (Leeper 2001; Blume 2007). The high voltages and currents in the electric power system create widespread exposures to ELF electric and MFs for electric utility workers and the general public. First, we discuss the main components of the electric power system that lead to ELF-EMF exposures (Blume 2007).

Generating Stations. Power from coal, oil, gas, hydro, nuclear fission, solar, and other renewable sources run electric generators in these plants. High MF exposures occur around generators, transmission lines, substations, and especially *bus bars*, the wide copper bars that carry thousands of amperes between the generators and the transmission substation. High EFs are found in the transmission substations and under the high-voltage lines that transmit electric power to distant customers. Although EMF exposures at generating stations can be high, most of the structures are occupied by the power sources such as steam, hydroelectric, and solar where EMF exposures are low or moderate (Table 7.2).

Transmission Lines. *High-voltage transmission lines* (HVTLs) transport electricity at voltages from 250 to 740 kV over long distances from a power plant to a local electric grid. HVTLs are generally overhead lines, but underground HVTLs are sometimes used in larger cities.

TABLE 7.1

Selected Benchmarks of ELF-EMF Exposures with Their Most Prominent Adverse Health Effects

Health Risk	Specifics	Metric	MF Limit (μT)	EF Limit (kV/m)
Neurologic effects	Threshold L (ACGIH 2001)	Maximum rms vector magnitude	1000[a]	92[a]
	High action level (EU 2013)		6000[b]	20[b]
Electromagnetic interference with pacemakers and other implants	Threshold limit value (ACGIH 2001)	Maximum rms vector magnitude	100	1
Cancer	Childhood leukemia (IARC 2002)	TWA ELF resultant	0.30[c]	Inadequate associations
	Occupational cancers (Bowman et al. 2013)		0.28[c]	

[a] Frequency-dependent limit at 60 Hz.
[b] Frequency-dependent limit at 50 Hz.
[c] Lower bound on exposure category with significant associations.

TABLE 7.2

Population Statistics for Selected ELF-EF and MF Exposures in Electric Utilities

	ELF-MF Resultant (μT)		ELF-EF (V/m)
Source	**GM/Values**	**P95/Max**	**Range**
Generator bus bar	8.82	37.23	
Boiler house	0.09	0.36	
High-voltage transmission lines			10,000–32,000
—Bare-hands work		2200	
—De-energized lines	12–942		
—Ground work	1.80		
Substations	4.68	156	15,000–47,000
Underground vaults	9.00	7700	
Administration building	0.04	1.18	
Occupation—Environment		**GM of TWAs**	
Mechanic—generating station	1.03		8.10
Plant operator—generating station	0.85		7.58
Electrician—substation	1.82		—
Lineman—HVTL (live line)	1.44		174.64
Lineman—distribution lines	1.39		10.95
White collar jobs—office	0.19		11.09

Note: A selection of measurements from the literature (Bracken et al. 1997, 2001, 2005; Guenell et al. 1996; Kelsh et al. 2000; Korpinen et al. 2009, 2011; Renew et al. 2003) summarized by the GM and P95 over a study population. Where population statistics are not available, the range, maximum, or single values are reported.

Substations. Distribution substations receive power from an HVTL, pass it through *step-down transformers*, and distribute it at lower voltages through several subtransmission lines or primary distribution lines with voltages from 2 to 35 kV. Substations are usually above ground, but they are also placed in underground vaults. The highest EFs occur in open substations where high-voltage lines and bus bars are uninsulated, as opposed to substations in buildings and underground vaults where insulation is often needed for safety.

Distribution Lines. A network of primary lines carries the power from substations to customers with their own transformers (industries, large commercial stores, and apartment buildings) and to neighborhoods with residences and smaller commercial customers. Along primary lines, small transformers are periodically mounted on a pole for overhead lines or in a cabinet for underground lines to step down the voltage to the levels used by appliances and other electrical equipment (120–600 V in different countries). Secondary distribution lines carry this low-voltage electricity to individual residences or commercial customers. The lower the voltage and the more urban the environment, the more likely distribution and transmission lines will be underground.

With work on overhead power lines, the main determinants of EF exposures are the line voltage and the worker's proximity to energized lines. Distances to energized lines are generally longer in Europe where the safety rules require power lines to be de-energized (dead lines) before maintenance work is performed (CENELEC 2004). In contrast, electric utilities in North America perform maintenance on live lines by the use of insulated gloves for lower voltages and "hot sticks" (insulated tools mounted on fiber glass poles) for higher voltages. The most extreme EMF exposures in electric utilities come from "bare-hands" work on live HVTLs (Bracken et al. 1997). To avoid exceeding the 20-kV/m safety limits, bare-hands workers wear metallic suits that shield them from the EFs.

MF exposures from electric line work are also determined by the distance from energized lines (either the line being repaired or neighboring lines) as well as the line current. Because bare-hands work on HVTLs requires proximity to live lines with currents >1000 A, this work practice again produces the highest MF exposures with a maximum of 2200 μT (Bracken et al. 1997).

Personal Exposures of Electric Utility Workers

Electric utility workers have the greatest EMF exposures from the electric power system because they are often (1) closer to the wires, (2) unshielded from EFs, and (3) exposed to electric shocks (ranging from nuisance to injurious) and *contact currents*, currents that flow between their hands and feet when touching surfaces with different electrical potentials. Note that shocks and contact currents inject ELF-EFs into the body, just as external EMF exposures do by induction (Bracken et al. 2009).

Table 7.2 gives a selection of ELF-EMF exposures by source or environment compared with personal TWA exposures. HVTLs and substations (both above and underground) are the greatest sources of exposures, followed by generating stations and distribution line work. The full-shift TWAs are substantially less than the exposures in a comparable environment, especially for power line work where the discrepancies are an order of magnitude or more. The discrepancy in EFs is due in part to the field's distortion by the worker's body during personal monitoring, whereas source measurements are made without the worker.

This large difference between MF exposures near sources and the TWAs is probably due to the long periods of time that line workers spend assembling supplies, traveling to the work site, and working underneath the power line (ground work). When the background MFs are far less than the exposures from working close to a strong source, the 8-hr TWA ELF-MF is approximately

$$TWA\left[B_{ELF}\right] \cong r\bar{B}_{hi} \quad T/8\,hr \tag{7.8}$$

where $\bar{B}_{hi}$ is the average exposure in the high field environment near the source, ΔT is the task's duration, and r is the rate of repetition for the task. This is a useful rule-of-thumb for modeling TWA exposures from spot measurements near strong sources.

Summary of Electric Power Systems

- Important components of the electric power system are generating station, bus bars, substations, transformers, HVTLs, distribution lines, and grounding systems.
- Determinants of ELF-MF exposures from electric lines are the current, degree of cancellation, distance from the line, and duration of work near the line.
- Determinants of ELF-EF exposures from electric lines are the voltage, distortion, and/or shielding by metal objects exposure duration; and distance from energized lines.
- Electric shocks, contact currents, and ELF-EMF all induce EFs inside the body.

Residences

Sources

The principal residential sources of ELF-MF are appliances and the electrical distribution system. Nearby transmission lines, distribution lines (primary and secondary), and transformers in larger apartment buildings all emit ELF-MFs. Several of these power lines are adjacent to a typical home, averaging 3.1 lines per residence in Los Angeles County as an example (Bowman et al. 1999). A line's contribution to the home's ELF-MF distribution depends on its distance, location (overhead or underground), current, and the degree of MF cancellation between the wires, which is optimal if the line has no neutral wire.

Another source of ELF-MF is currents from water pipe grounds. Grounding systems are deployed throughout the electric power system to minimize danger and damage from equipment failures, lighting strikes, and accidental shocks to workers and the public (Blume 2007). In addition to large surges from lightning and major faults, ELF-MF is emitted by the small ground currents that constantly pass between electrical components to keep all their neutral wires at zero potential. In residences and commercial buildings, ground currents can be a significant MF source if the *system ground* is provided by bonding the building's neutral wires to a metal water pipe—an arrangement found in 36% of U.S. residences (Zaffanella 1993). Water pipe grounds create circuits whose MF emissions are not cancelled by MF vectors from adjacent conductors (Leeper 2001).

Consequently, residential ELF-MF vary widely from minimal exposures (<0.01 μT) to fields above 0.3 μT throughout the home or only in "hot spots" close to interior ground currents or exterior power lines with high currents. The ELF-MF exposures from selected power system sources are summarized in Table 7.3. This massive interresidence variability in ground current MFs (GM = 0.01 μT & P95 = 0.70 μT → GSD = 13.2) is due to factors such as metal versus plastic water pipes, the distance from living areas to water pipes carrying ground currents, and residential electric wiring practices that determine the proportion of home's neutral currents diverted to ground currents (Zaffanella 1993).

Residential ELF-MFs also display a diurnal cycle as currents in power lines fluctuate with their customer's daily activity cycle, air conditioner use, or both (Kaune et al. 1987; Zaffanella 1993). The same factors can create exposure variability over the seasons and between weekdays and the weekend. Thus, exposure assessment errors in epidemiologic studies can be reduced by adjusting residential measurements for the time of day, day of the week, and season.

Table 7.3 also summarizes average ELF-MFs in homes where exposures are lower in Europe than in North America. This can be explained by differences in the electrical distribution system where overhead distribution lines are more common in North America (77% in the United States vs. 15% in the United Kingdom). The minimal residential MF in Norway is attributed to secondary lines with no neutrals that create balanced currents by conservation of energy and therefore maximal cancellation of the MF from the phases (Mild et al. 1996).

Another component of residential MF is *high-frequency transients* (HFTs). The abrupt surge of electricity from flipping a switch produces HFTs in electrical circuits. Transients with frequencies from 60 Hz to 50 MHz and magnitudes up to 3 μT have been measured in residential MF (Guttman et al. 2001). A cruder approach is to measure a room's HFT with a Microsurge meter plugged into an AC wall socket (Havas and Stetzer 2004). This "dirty electricity" meter measures the voltage's rate of change (in units of volts per second) in the 4–150 kHz band.

TABLE 7.3

Selected Residential Exposures to ELF-MFs by Power System Sources, Country, and Area versus Personal Monitoring

	24-hr TWA of ELF-MF (μT)	
Power System Source[a]	**GM**[b]	**P95**[c]
Apartment building transformers	0.59	1.30
Transmission lines	0.09	0.49
Overhead primary lines (no neutrals)	0.02	0.60
Overhead secondary lines	0.04	1.58
Underground distribution lines	0.03	0.50
Ground currents	0.01	0.70

	Area		Personal	
Country	**(Range of GMs)**		**GM**	**P95**
United States	0.06–0.07		0.089	0.389
Canada	0.05–0.11		0.081	0.360
United Kingdom	0.036–0.039	Europe	0.037	0.311
Germany	0.029–0.047	Europe	0.037	0.311
Norway	0.011–0.015	Europe	0.037	0.311

[a] Random survey of U.S. residences. (Zaffanella L. E., *Survey of Residential Magnetic Field Sources*, Volume 1:Goals, Results, Conclusions, EPRI Report No. TR-102759, Electric Power Research Institute, Palo Alto, CA, 1993.)
[b] GM ≈ Median over 24 hr and all rooms in the residence.
[c] P95 in the 5% of rooms with the highest MF.

Although dirty electricity measurements have not been correlated with MF exposures, they have been used in epidemiologic studies (Havas 2008; Milham and Morgan 2008).

As for ELF-EFs, HVTLs adjacent to homes are potential sources, but their EFs are shielded effectively by all materials, including the walls and insulation of household wiring. U.S. epidemiologic studies measured low ELF-EFs inside homes with GM = 4.4 V/m that were not correlated with the characteristics of nearby power lines (Kaune et al. 1987; Barnes et al. 1989; London et al. 1991).

Appliances and other electric equipment in homes also emit ELF-MFs either as a by-product of their currents (e.g., light, heating, and most electronics) or because electromagnetism is an essential part of their design (e.g., electric motors and the *cathode ray tubes* [CRTs] used in older televisions and computer monitors). The MF magnitude from appliances also decreases with distance from the source; but unlike power lines, the decline is proportional to $1/r^3$ (Preece et al. 1997).

Table 7.4 shows a sample of the MF emissions from residential appliance at distances where the head and trunk are likely to receive greater cumulative exposures (Behrens et al. 2004). Generally, appliances whose functioning depends on MFs have stronger emissions than others with comparable electric power. The reason is that electric motors and the other electromagnetic appliances have coils with multiple turns of wire whose number is directly proportional to the emitted MF from a given current. With CRTs, the MF systematically sweeps the cathode ray (an electron beam) across the screen horizontally at 15.75 kHz and vertically at 60 Hz (Kaune et al. 2000), so older TVs, computer monitors, and video games emitted both intermediate frequency and ELF-MFs. CRT monitors are now

TABLE 7.4

Selected ELF-MF from Home Appliances at Distances Typical of Personal Exposures

	Close (5 cm)		Manual Work Distance (0.5 m)		Far (≥1 m)	
Type	**Median**	**P95**	**Median**	**P95**	**Median**	**P95**
Light			Fluorescent lamp			
			0.10	0.34	0.02	0.08
Heat	Hair dryer		Electric range		Baseboard heater	
	13.01	45.82	0.07	0.22	0.04	0.09
			Electric oven			
			0.82	1.62		
Electronics	Cell phone[a]		Clock radio		Stereo	
	6.00	10.76	0.01	0.06	0.01	0.07
			Microwave			
			0.67	1.15		
Electric motors	Electric razor		Electric can opener		Heat pump	
	164.75	—	1.67	2.15	0.07	0.28
MF-based electronics			Computer w/CRT[b] monitor		TV with CRT	
			0.13	0.27	0.02	0.06
			Induction range[c]			
			1.00	1.72		

[a] 217 Hz pulses converted to rms.
[b] CRT, cathode ray tube.
[c] ELF modulation of 20–50 kHz carrier waves (total MF = 0.4–2 μT at this distance).

being replaced by plasma and liquid crystal displays with much lower ELF-MF emissions in more developed countries.

Table 7.4 includes cell phones and induction cooking stoves, whose ELF-MF emissions supplement to their better-known high-frequency EMF. The RF signals from 3G and 4G cell phones are emitted as 217 Hz pulses. The current from the phone's battery therefore pulses at the same rate and produces pulsed DC MFs that are predominantly in the ELF frequency range but with some higher harmonics (Tuor et al. 2005). Induction ranges cook food in metal pots with strong MF that consist of 20–50 kHz *carrier waves* with ELF *modulation* (Stuchly and Lecuyer 1987), similar to amplitude-modulated (AM) radio signals.

Personal Residential Exposures

Personal TWA MF exposures at home are determined by the duration of appliance use as well as the fields from the power distribution system and appliance emissions (discussed above). One-third of an adult's cumulative ELF-MF exposures are reportedly from home appliances, with higher proportions for children (Swanson and Kaune 1999; Behrens et al. 2004). This trend can be seen in Table 7.3 that compares the GMs of the 24-hr TWAs of the ELF-MF resultant from area and personal monitoring.

Summary of Residences

- The main determinants of residential ELF-MF exposures are the electric power system (including water pipe grounds as well as power lines) and appliance use.

- Appliance sources of ELF-MFs are lighting, heating, electronics, electric motors, and the direct use of MFs in applications such as induction cooking ranges.
- EFs in residences are low and not affected by outside electric lines.

Schools and Offices

Sources

Like residences, the primary sources of ELF-EMFs in schools and offices are the electrical distribution system (both outside and inside the building) and the electrical equipment that, in many cases, are similar to residential appliances. For example, the leading sources of ELF-MFs in California public schools (Enertech Consultants 1999) had 24-hr TWA exposures (Table 7.5) that mostly overlapped the comparable fields at homes (Table 7.3). The California school exposures are consistent with those measured in a Canadian school system (Sun et al. 1995) but higher than in Spanish classrooms (Tardon et al. 2002).

Additional MF sources in schools are fluorescent lighting, office equipment, and electrical panels (or switch boxes) that are all found in offices. An electric panel adjacent to an occupied room is often the greatest MF source in a school or office building. For example, the ELF-MFs near an electric panel attached to an outside power line were 13–70 µT in a U.S office building (Moss and Ragab 1995) and 0.88 µT in a Spanish school (Tardon et al. 2002).

Electrical equipment in schools and offices has ELF emissions that are, in many cases, similar to those of home appliances (Table 7.4). For example, ELF-MF emissions at working distances from computer monitors, photocopiers, scanners, FAX machines, and video projectors range from 0.05 to 0.14 µT. Most electrical equipment in offices are similar to those

TABLE 7.5

Selected ELF-MF Exposures in Schools

	GM (µT)	P95 (µT)
Leading Source	**24-hr TWA[a]**	
Ground currents	0.033	0.352
Distribution lines	0.024	0.063
Fluorescent lights	0.024	0.067
Electrical panel	0.023	0.117
Office equipment	0.023	0.073
Country	**Area Measurements**	
United States	0.040	0.210
Canada	0.033	0.281
Spain	0.014	0.037
Personal Exposure	**Full-Shift TWA**	
Students	0.078	0.197
Teaching occupations	0.114	0.399

[a] GM measured over 24 hr and all rooms in school. P95 measured in the school room with the highest MF.

in schools, but they often result in higher TWA exposures because they are used more frequently and are closer together than in schools.

Higher ELF-MF emissions have been introduced into offices, schools, and stores by computer servers, metal detectors, and electric article surveillance (theft detectors). For example, a room with banks of computers that service networks of personal computers for an office building had ELF-MFs ranging from 0.04 to 0.66 μT (Tepper et al. 1992). Metal detectors emit pulsed MFs with intermediate frequencies (1–100 kHz) that are perturbed by metal objects. Fixed metal detectors can have much higher MFs (up to 100 μT) than hand-held detectors (~5 μT).

Electronic article surveillance (EAS) devices detect electronic tags on books, clothing, and other articles by emitting EMFs with complicated waveforms that range from ELF to microwave frequencies. EAS systems also use EMF to deactivate the tags when the article leaves the facility and to reactivate it upon return. With EAS systems that use continuous wave ELF-MFs, measurements at the detector panels placed by doorways have GM = 340.5 μT with GSD = 2.07 and maximum = 843.9 μT (Moss and Roegner 1998; Harris et al. 2000; Cooper 2002; Trulsson et al. 2007; Joseph et al. 2012). The MF emissions from both EAS and metal detectors have very short ranges, so exposures are limited to people who use them regularly.

Personal Exposures in Schools and Offices

In a random survey of the U.S. population (Zaffanella 1998), the TWA MFs at schools (Table 7.5) are less than exposures at home (Table 7.3), work, and traveling. As in residences, the personal TWAs for students and teachers is higher than the area measurements in classrooms (Table 7.6), again showing that using electrical equipment is an important determinant of personal exposures. Personal ELF-MF exposures of workers in schools, offices, and a selection of other occupations are given in Table 7.6. These data were selected from a job–exposure matrix (JEM) of full-shift TWA measurements grouped by the 1988 International Classification of Occupations (ISCO) (Bowman et al. 2014).

The JEM is an essential tool for assessing exposures in retrospective chronic disease studies from contemporary measurements, historical data, expert judgments, or a combination. With the JEM for ELF-MF in Table 7.6, means and variances were calculated by pooling TWA measurements from multiple studies whose job titles were coded into the numerical ISCO system (ILO 1998). When the subjects' jobs also have ISCO codes, their exposures are then assessed by linking them to the mean exposures from the JEM. Variations of the JEM method are used by occupational epidemiologic studies described in Chapters 10 and 11.

Office occupations from the JEM (Table 7.6) provide a comparison of their TWA MF exposures with teaching professionals (from preschools to universities) and students (Table 7.5). A clear gradient in the MF GMs is apparent from students up to teachers and then to office jobs, probably due to how often electric equipment is used.

Note also that the students' P95 = 0.197 μT (Table 7.5) is above the GM = 0.15 μT for accounting, bookkeeping, and finance clerks (Table 7.6), showing that assessing exposures by the JEM means can create misclassifications in an individual's exposures. These *Berkson exposure assessment errors* result from assigning the JEM's mean exposure for an occupation to all subjects who held that job, and they can lead to both positive and negative errors in risk estimates (Carroll et al. 2006).

Despite these Berkson errors created by the JEMs, their ability to make unbiased quantitative assessments of exposures to an entire study population make them invaluable tools for occupational epidemiology.

TABLE 7.6

Personal Measurements of Full-Shift TWA ELF-MF Grouped by Selected Occupational Categories

Occupation	GM (μT)	P95 (μT)
Teaching professionals	0.11	0.40
Office Occupations		
Library and filing clerks	0.45	0.59
Accounting, bookkeeping, and finance clerks	0.15	0.87
Secretaries and keyboard-operating clerks	0.10	0.51
Manufacturing Occupations		
Ore and metal furnace operators	0.95	9.08
Sewing machine operators	0.83	1.88
Welders and flamecutters	0.80	8.93
Metal moulders and coremakers	0.52	6.08
Electrical and electronic equipment mechanics and fitters	0.23	2.30
Machinery mechanics and fitters	0.20	1.18
Food processing and related trades workers	0.14	0.85
Rubber and plastic products machine operators	0.11	0.39
Transportation Occupations		
Locomotive engine-drivers and related workers	13.26	65.65
Aircraft pilots	0.97	1.87
Ships' engineers	0.55	3.21
Ships' deck officers and pilots	0.22	1.06
Motor vehicle drivers	0.12	0.51
Transport laborers and freight handlers	0.10	0.37
Homemaker	0.06	0.08

Summary of Schools and Offices

- In schools and offices, sources of ELF-MF are generally similar to residential sources, but TWA exposures are usually higher because of the time using electric equipment.
- Students, on average, have less TWA exposures to ELF-MFs than teachers, who have less than office workers. However, exposure distributions overlap between these three groups.
- Although metal detectors and EAS (theft detectors) have introduced elevated MFs into schools, offices, and stores, their emissions have a short range, so exposures are limited to people who are near them regularly.

Transportation

Sources

Transportation has been a pervasive source of ELF-MF exposures since the beginning of the twentieth century, either from electric motors, the electrical components of internal combustion engines, or lighting and other electrical equipment inside the passenger compartment. Instantaneous MF exposures follow the same principles as other electrical equipment, and they vary inversely with the person's distance from the source (actually $1/r^3$ in most cases) and directly with its current, which is a function of the engine's power in electric transportation. The frequencies of transportation MFs vary widely within the 0–3000 Hz range due to the diversity of vehicle designs and with some designs, the frequency's dependence on the vehicle's speed.

Electric motors transport people and freight in many types of vehicles: intercity trains, urban rail, trolleys, subways, monorails, and battery-powered vehicles (e.g., hybrid cars, forklifts, milk delivery carts). Electric rail systems supply power to a vehicle either by a *third rail* or an *overhead line* (or *catenary*) whose electricity is carried to the train by a *pantograph.* The traction motors that power a train can be located either in locomotives or in individual passenger cars. After the current powers the traction motors, the electric circuit is completed through the train's metal wheels touching the regular rails. (Rubber-tired electric buses and trolleys close their traction circuits through a double pantograph contacting hot and neutral overhead lines.) Even a diesel locomotive can have substantial MF emissions because they have a *hybrid power system* with the diesel engine connected to a generator and traction motors at each axel that turns (or brakes) the wheels. These high currents on the rails and overhead catenary lines also expose railroad maintenance workers (Wenzl 1997; Yost 1999) and people living along the line (Brix et al. 2001) to EMF at the rail line's power frequency, which can be 0, 16.66, 25, 50, or 60 Hz in different countries and rail systems.

The proximity of electric rail passengers and crew to the traction motors and power circuit is a major determinant of their MF exposures. Trains with overhead lines tend to have higher MF exposures to the head and trunk, whereas those with third rails concentrate the exposures at the feet. Passengers have higher exposures near the traction motors in self-propelled rail cars than in trains with locomotives.

The traction motor's power is another determinant of MF exposures on electric vehicles. This relationship with locomotive power can be seen indirectly in a Swiss study where the electric locomotive engineers had higher exposures on alpine routes versus lowland routes and from hectic driving versus calm driving (Röösli et al. 2005). These higher exposure conditions both require greater locomotive acceleration and therefore greater traction motor power. Consequently, a logical hypothesis is that ELF-MF exposures from electric vehicles and all electric motors should generally increase with the motor's peak power that can usually be obtained from the equipment's specification information in manuals, name plates, or the Internet. However, this hypothesis has never been tested.

Finally, ELF exposures from electric transportation depend on whether the input electric power and traction motors are AC or DC—all four combinations are in use (e.g., AC power with AC motors, DC power with AC motors). With trains, the electrical and electronic circuit components that control the speed and convert current between AC and DC affect both the MF magnitude and frequency spectra (Chadwick and Lowes 1998; Dietrich and Jacobs 1999) and have changed historically as solid-state electronics have been developed for large currents and motors (Muc 2001). Note that an electric motor's rotating *armature* creates an oscillating MF even if it runs on DC currents. For example, battery-powered vehicles such as forklifts and milk delivery carts usually have static MF emissions near the battery and ELF-MF emissions near the motor.

Cars, buses, trucks, motorcycles, and other vehicles with internal combustion engines also emit ELF-MFs with a bewildering array of frequencies from their ignition system, the rotation of magnetized metal parts in the drive chain (including steel-belted radial tires), electric motors (e.g., fans), electronic components, and the MG-MFs from driving by steel structures (see section "Personal Transportation Exposures"). With motorcycles, MF emissions were traced to the engine's spark ignition system, located very close to the rider's groin (Chipkar 2007).

Personal Transportation Exposures

Table 7.7 summarizes the TWA ELF-MF exposures for the drivers and passengers in transportation vehicles, as well as maintenance workers on electric rail tracks. The JEM (Table 7.6) also has TWAs for selected transportation occupations.

The highest exposures were measured with intercity electric locomotive engineers, due to their proximity to the locomotive's high-powered traction motors, the catenary lines overhead, the neutral-return rail beneath, and the power circuits carrying high currents through the locomotive. Among railroad engineers, the Swiss exposure were the highest because of the magnetic induction forces needed to pull a train up an alpine pass and brake it on the way down. Remarkably, the "regenerative braking mode" that slows the locomotive by generating electric power emitted an 80% greater ELF-MF on average than climbing an alpine pass with the same slope (Röösli et al. 2005). In nonalpine countries, the passengers on intercity electric railroads had a GM exposure half that of the engineers because they also sat between the catenary lines above their car and the neutral return-rails below, even though the traction motors were far away in the locomotive.

Urban electric transit had MF exposures roughly an order of magnitude less than its intercity counterparts, probably due to the lower power needed to move a light rail train through a city. The one exception is the P95 = 11.31 μT for urban electric transit passengers that presumably occurred when they sat over their car's traction motor.

In addition, maximum exposures over 10 μT were measured on a maintenance crew for an intercity electric rail line, the operator of a battery-powered forklift, and a motorcycle rider. These high exposures can be explained for the first two sources because of the heavy loads moved by intercity trains and forklifts. However, the maximums above 20 μT

TABLE 7.7

Selected ELF-MF Exposures from Common Forms of Transportation

	TWA ELF-MF (μT)	
	GM	P95/Max
Swiss electric passenger train engineers	27.00	200.00
Other intercity electric train engineers	5.31	22.64
Electric intercity train passengers	3.08	6.25
Intercity electric rail maintenance	1.18	17.80
Urban Electric Transit (including Subways)		
—Engineers	0.29	1.40
—Passengers	0.81	11.31
Urban electric rail maintenance	0.19	0.83
Internal combustion vehicles (cars, buses, vans, pickup trucks)	0.19	0.80
—Hybrid cars	0.46	8.43
Motorcycles[a]	6.50	>20
Battery-powered forklift operator	1.17	125.00
All transportation (U.S. survey)	0.096	0.27

[a] Spot measurements with a single-axis MF meter.

measured on large "cruiser" motorcycles (Chipkar [2007] 2011) are much greater than the exposures from other internal combustion engines (Table 7.7) and can best be explained by the rider's proximity to the engine.

The transportation statistics in Table 7.7 were largely derived from a small number of measurements and are thus poor representatives of population exposures, especially given the complex and diverse transportation technologies reviewed above. The one exception is the "1000 Person" random survey of the U.S. population (Zaffanella 1998) where the TWA ELF-MF during travel had GM = 0.096 μT (P95 = 0.273 μT). This is more than home exposure in the U.S. survey (GM = 0.08 μT; P95 = 0.389 μT) but less than work exposures (GM = 0.103 μT; P95 = 0.500 μT). In the transportation occupations selected from the JEM (Table 7.6), the locomotive engine drivers, airline pilots, ships' engineers, and motor vehicle drivers had GMs greater than 85% of all other occupational categories (Bowman et al. 2014). (In making comparisons between Tables 7.6 and 7.7, note that the power frequency in transportation equipment can vary from 16.66 Hz in some electric railroad systems to 400 Hz in airplanes (Dietrich and Jacobs 1999), so these data might not accurately indicate biologic effects due to frequency dependence of magnetic induction. (Equation 7.1))

Summary of Transportation

- Important determinants of ELF-MF exposures from rail transportation are the power of the electric traction motors, the time spent close to the motor, the power circuit (the circuit within the vehicle from the electrical source to the traction motor and back to ground), or a combination of the above.
- The frequencies in transportation ELF-MF vary widely, due to both the electrical system's design (e.g., AC, DC) and the oscillating MF emitted by an electric motor's armature.
- The ignition system of an internal combustion engine can create elevated ELF-MF exposures with people who spend large amount of time close to the engine, such as motorcycle riders and chain saw operators (see section "Manufacturing and Other Occupations").

Manufacturing and Other Occupations

Sources

In manufacturing plants and other economic sectors, most electrical equipment use the five physical mechanisms outlined for home appliances (Table 7.4): light, heat, electronics, electric motors, and the direct use of MFs. However, manufacturing technologies can use electric currents that are orders of magnitude greater than home appliance currents, with similar increases in their MF emissions. For example, electric resistance furnaces for refining steel operate on the same principle as the electric ovens in kitchens, but their maximum reported emission is 8000 μT (Table 7.8) versus P95 = 1.62 μT for kitchen ovens (Table 7.4). Similarly, induction furnaces for metal heat treating emit a maximum of 8367 μT, whereas induction cooking ranges have P95 emissions = 1.7 μT.

Some MF sources in manufacturing use technologies not found in residences. Iron's ferromagnetic properties lead to some high ELF-MF exposures in many kinds of metal

TABLE 7.8

Selected TWA MF Exposures from Working with ELF Manufacturing Sources

Source	GM (μT)	Maximum (μT)
Metal Welding		
Spot resistance welding	967.50	11,436.8
Manual metal arc welding	141.42	
MIG (metal inert gas) arc welding	79.37	
TIG (tungsten inert gas) arc welding	12.68	141.4
Metal Heating		
Electrical resistance furnaces	567.27	8000.0
Induction heaters/furnaces[a]	9.85	8366.6
Electrochemical Processes[b]		
Rectifier room	69.62	781.2
Chlorine electrolysis cells	13.34	126.8
Metal electroplating	2.49	
Machining, Fabrication, etc.		
Nondestructive testing	14.66	5636.8
Sewing machine	0.83	11.05
Semiconductor fabrication	0.67	26.7
Machining operations (lathes, etc.)	0.45	
Battery charger	0.38	
Plastics extruder	0.23	
Chemical mixing machine	0.16	

[a] Intermediate frequency (3 kHz–10 MHz) induction heaters and furnaces.
[b] ELF component of static MF with an AC "ripple."

machining and fabricating. Because grinding magnetizes steel parts, degaussers remove this undesirable property by passing strong AC currents through the parts (Wenzl et al. 1997). Degaussers are also used to demagnetize steel parts after fault detection with magnetic fluorescent particles. Another form of nondestructive testing passes strong AC MFs through a steel part, exposing the operator to high MFs (Table 7.8).

Electrochemistry uses DC electricity to change salts into elements. Two examples are the *electrolysis* of NaCl (table salt) into chlorine gas and the chrome plating of metal parts. For industrial electrochemical processes, the DC electricity is generated by passing three-phase AC electricity through *rectifiers* that leaves an AC "ripple" on top of the DC current. Because the AC ripple degrades the electrochemical process, as in aluminum refining, the current is passed through many banks of rectifiers, leaving essentially pure static MF (Moss and Booher 1994). This ripple creates high exposures in the rectifier room and along the cells or tanks where the electrolysis takes place. As shown in Table 7.8, electroplating typically has much lower MF exposures than electrochemical plants that can use as much electricity as a medium-sized city (~60,000 A).

The list of ELF-MF sources in manufacturing (Table 7.8) is topped by metal welding, not the familiar *arc welding* but *spot resistance welding* used to bond steel plates in automobile bodies and other metal parts. Over the many types of welding, the applied current and the welder's distance from the current are major determinants of MF exposures. The frequency spectra of the welding currents varies immensely over welding technologies, involving DC, 50/60 Hz, its harmonics, and even RF.

Metal furnaces and heat treating equipment come next on the list, and also vary widely in current, frequency spectrum, and distance to the worker. *Resistance furnaces* in electrosteel plants use thousands of amperes, but their high temperatures keep workers at a distance, thereby moderating TWA exposures. Heat treating by magnetic induction localizes the high temperature to the metal part inside the solenoid, so TWA exposures are often elevated for operators of *induction furnaces* and *induction heaters*.

The lower exposures in Table 7.8 come from electric motors in, for example, sewing machines, lathes, and mixing machines. With motorized processes, the usual determinants of ELF-MF exposure (motor power, distance to the worker, and frequency spectrum) are moderated by the motor speed, which increases MF emissions, and the process's noise, which generally decreases the duration of exposure and thus the TWA. Among electric motors, the higher emissions from sewing machines with their high-speed motors (Table 7.8) are noteworthy because operators are predominantly women.

Personal Exposures in Manufacturing and Other Occupations

Workplaces have the highest personal ELF-MF exposures (GM = 0.103 μT; P95 = 0.500 μT) in the random survey of the U.S. population (Zaffanella 1998). The economic sectors with the highest occupational MF exposures are electric utilities (Table 7.2), transportation (Table 7.7), and manufacturing (Tables 7.6 and 7.8). Among the most exposed occupations in the ELF-MF JEM (Bowman et al. 2014), the only occupation from another sector is forestry workers and loggers (GM = 0.76 μT; P95 = 9.69 μT), presumably from their proximity to internal combustion engines of portable chain saws. Among the least exposed occupations are homemakers in the United States (GM = 0.06 μT; P95 = 0.08 μT); producers of market-oriented crops and animals (GM = 0.03 μT; P95 = 0.25 μT); childcare workers in the United Kingdom (GM = 0.03 μT; P95 = 0.17 μT); and operators of bleaching, dyeing, and cleaning machines (GM = 0.03 μT; P95 = 0.05 μT).

Summary of Manufacturing and Other Occupations

- The highest ELF-MF exposures in manufacturing are from spot resistance welding, resistance furnaces, induction heaters and furnaces, electrolysis, and magnetic nondestructive testing (NDT) of metal parts.
- The physical principles used in manufacturing ELF-MF sources are similar to home appliances (except for arc welding and NDT), but the currents and therefore the MF emissions can be orders of magnitude greater in manufacturing.
- The noise from large electric motors and the heat from electric furnaces reduce the TWA ELF-MF exposures because they tend to keep workers away at a distance.

Motion Gradient Magnetic Fields

Sources

The trace of the MF vector in Figure 7.2 is approximately helical, due to the lineman's motion through an MF gradient from perturbation of the geomagnetic field by steel objects. Although a pervasive part of the low-frequency MF environment, these MG-MFs are seldom considered in health studies because EMDEX-type instruments were designed to measure fields from power lines and therefore filter out frequencies <40 Hz. However, MG-MF magnitudes can be larger than other ELF-MF exposures where there are large steel structures, rapid motion, or strong DC MFs.

The ultimate example of an MG-MF comes from head motion in the spatial gradients of the DC MF around magnetic resonance imaging (MRI) scanners and has been shown to cause loss of balance, cognitive disturbances, and other neurologic disturbances (de Vocht et al. 2003; Glover et al. 2007; van Nierop et al. 2012a,b). These neurologic studies were conducted in MF gradients of 1–2.5 T/m close to 1.5 and 7 T MRIs (de Vocht et al. 2003). (Note: These spatial gradients in the static MF are different than the MRI's *gradient fields* that are pulsed MFs whose amplitudes gradually change along the length of the scanner's bore.)

The far more common source of MG-MF is the static geomagnetic field, whose main fields range from 30 μT near the equator to 60 μT near the poles (Campbell 1997). The geomagnetic field magnetizes steel structures that then perturb the static MF in their vicinity. Although MG-MFs in workplaces have not been studied systematically, their presence is indicated by a factory survey where the static MF at work locations (medians = 24.2–46.2 μT) were well below the local geomagnetic field of 55.0 μT (Bowman and Methner 2001). Therefore, steel in factories must be producing these large MF spatial gradients, exposing workers to MG-MF as they move through the plant. MG-MFs were also detected in cars, trucks, and buses as they drove by steel structures on the side of the road (Dietrich and Jacobs 1999).

Personal Exposures to MG-MFs

The most compelling explanation for loss of balance reported in the MG-MFs around MRIs (van Nierop et al. 2012b) is their induction of currents in the ionic fluids of the semicircular canals, the body's balance sensors (Glover et al. 2007; Roberts et al. 2011). According to the induced current mechanism (Equation 7.1), these ionic currents in the balance organs should be proportional to MF-MG's peak time derivative, dB_{MG}/dt. An alternative metric for MG-MF is its rms vector magnitude (Equation 7.5) that in combination with $\mathbf{B}_0$ and B_{ELF} also appears relevant to magnetoreception mechanisms by which animals navigate through MF gradients (Vanderstraeten and Gillis 2010).

Exposures to these two MG-MF metrics are given in Table 7.9. The most comprehensive data comes from exposure measurements with three-axis MF probes in a helmet on health care workers performing standard tasks in MRI scanner rooms (Groebner et al. 2011). In this study, the maximum Peak[*dB/dt*] was 1,400,000 μT/s. For perspective, a single-frequency sinusoidal MF has

$$\text{Peak}\left[dB/dt\right] = 2\pi f^2 \text{RMS}\left[B_{ELF}\right] \tag{7.9}$$

TABLE 7.9

Exposures to MG-MFs, Measured as TWAs of the RMS Vector Magnitudes for B_{MG} and Its Peak Time Derivative dB_{MG}/dt

	B_{MG} (μT)		dB_{MG}/dt (μT/s)	
Source	**GM**	**P95**	**GM**	**P95**
Working with MRIs	—	—	310,000	1,310,000
Riding a bucket truck next to a distribution line (see Figure 7.2)	0.98[a]	—	26.6[a]	—
Driving on city streets, rural roads, and expressways	0.50	1.87	—	

[a] Single measurement.

so this maximum MG-MF exposure for the MRI workers is the same in terms of magnetic induction as a 2600 μT_{rms} ELF-MF at 60 Hz—an exposure between the maximums ELF magnitudes from rectifier rooms and non-destructive testing in Table 7.8.

On the low end of the scale, MG-MFs from geomagnetic fields have not been studied systematically with the exception of a few surveys with the extinct Multiwave instruments. The vector trace in Figure 7.2 was measured with personal Multiwave III monitor and analyzed with Fourier transform techniques (Bowman et al. 2010). As shown in Table 7.9, the rms vector magnitudes of the MG-MF in this sample are 0.98 μT for B_{MG} and 26.6 μT/s for dB_{MG}/dt. For the power–frequency and harmonic components in this line worker measurement, the rms vector magnitude = 0.81 μT, a value that is slightly less than the MG-MF, but dB/dt = 337.2 μT/s, a value that is an order of magnitude greater than the MG-MF. In other words, magnetic induction effects that depend on the dB/dt metric will be little affected by the MG-MF in this case; but to assess mechanisms affected by the rms vector magnitudes, measurements of both the MG-MF and power–frequency components should be taken.

A second source of geomagnetic gradient field exposures was found by Multiwave MF monitoring of internal combustion vehicles (Dietrich and Jacobs 1999). Although the ELF-MF exposures reported in the *Transportation* section (Table 7.7) were attributed to the sources inside the vehicles, their survey data for the five vehicles consistently recorded frequency spectra that were attributed to MG-MFs from passing steel objects along the road. The TWA MG-MF from these test drives had a GM that is similar to the line worker's exposure in the bucket truck (Table 7.9). The MG-MF's maximum rms vector magnitude (11.16 μT) was measured when the vehicles drove on toll-free Interstate expressways, where they were likely due to passing under steel-reinforced concrete bridges at speeds around the U.S. limit (55 mi/hr = 88.5 km/hr). Obviously, the person's velocity is a determinant of MG-MF exposures. However, the strength of the MF gradient near the steel object is also a factor, and this depends on the steel's mass.

Comparing the MG-MF exposures in Table 7.9 with the ELF-MF exposures in residences (Table 7.3) and occupations (Table 7.6) suggests that MG-MF should not be neglected in assessing ELF-MF exposures in the environment, especially if biophysical mechanisms other than magnetic induction are important. The impact of this exposure assessment error on epidemiologic findings has never been studied.

Summary of MG-MFs

- MG-MFs are ELF fields caused by a person's motion through spatial gradients in the earth's MF near steel objects or from strong DC MF sources, such as MRIs.
- Determinants of MF-MF exposures are the person's velocity and the steepness of the MF gradient around the steel object or the DC MF source.
- Even though MF-MG exposures are very common and near MRIs have neurologic effects such as the MFs from AC electricity, MG-MFs are filtered out by the EMDEX meters used in ELF-MF epidemiologic studies. Whether this exposure assessment error affects epidemiologic results has never been studied.

Concluding Reflections

At the conclusion of this chapter, the broad diversity of ELF-EMF sources and personal exposures is clear. Table 7.10 gives an impression of that diversity by contrasting high and

TABLE 7.10

Overview of ELF-MF Exposures by Environment, Contrasting Dynamic Ranges within and between Sources, and TWA Personal Exposures

		Sources			TWA from Personal Exposures		
Environment		**GM [μT]**	**Max [μT]**	**Hi:Lo GM Ratio**	**GM [μT]**	**GSD**	**Hi:Lo GM Ratio**
Electric utilities	Hi	Underground vaults			Mechanics in substations		
		9.00	7700		3.8	—[a]	
	Lo	Reactor buildings			Clerical occupations in generating stations		
		0.02	0.06	450	0.14	—[a]	27
Residences	Hi	Hair dryers			US survey of home exposures (not in bed)		
		13.01	45.82		0.09	2.12	
	Lo	Ground currents (household median over space and time)			European 24-hr surveys		
		0.01	0.12	1301	0.04	2.96	2
Schools and offices	Hi	Electronic article surveillance			Library and filing clerks		
		76.2	843.9		0.45	1.16	
	Lo	Spanish classrooms			Teaching professionals		
		0.01	0.18	5443	0.11	1.89	4
Transportation	Hi	Swiss electric locomotives			Locomotive engine-drivers		
		13.26	195		13.26	2.26	
	Lo	Pickup truck with gasoline motor			Motor vehicle drivers		
		0.06	1.08	221	0.12	2.09	111
Manufacturing	Hi	Induction heaters and furnaces			Ore and metal furnace operators		
		141.84	8366		0.95	3.17	
	Lo	Chemical mixing machine			Rubber and plastic products machine operators		
		0.16	—	887	0.11	1.93	9
Motion gradient magnetic fields	Hi	Open MRIs			MRI technicians and physicists		
		$B_0 < 8$ T			0.31 T/s	2.09	
	Lo	Metal in geomagnetic fields			Gasoline vehicle passengers		
		$B_0 = 20 - 60$ μT		200,000	8.59 μT/s	1.96	36,100

Note: Within an environment, the dynamic ranges are given as the ratio of the geometric means between the high- and low-exposure situations. For personal exposures, the dynamic range within an occupation or region is given as the GSD.

[a] GSDs are impossible to estimate from Kelsh et al. (2000) because SEs are given without sample sizes.

low MF exposures in the five environments around which this chapter is organized (plus the MG-MF). Among other insights, these comparisons show that the high:low (Hi:Lo) ratios of ELF-MFs for sources within an environment are greater by at least an order of magnitude than the ratios for personal TWA exposures. This again suggests that people are not generally near high MF sources for long periods of time. Of the five environments surveyed, residences, schools, and offices have lower MF exposures, whereas high exposures are more likely to occur in electric utilities, transportation, and manufacturing. The transportation sector has the greatest variability with the Hi:Lo ratio for personal exposures = 111.

The comparisons in Table 7.10 also give some perspective on the statistical power of ELF-MF epidemiologic studies in these five environments and the populations with high and low exposures. Because power increases with the difference between high and low exposures if the sample size and other design factors are constant (Kelsey et al. 1996), the GSD is an indicator of the power of a study that assesses exposures for each subject in its study population. For example, studies of residential MF should have lower power in the United States (GSD = 2.12) than in Europe (GSD = 2.96) (although the higher GM in U.S. homes might be a countervailing factor). For occupational studies that assess exposures by a JEM within an environment, the ratio of the high GM to low GM likewise indicates a study's power. Therefore, a study in an electric utility where the Hi:Lo ratio = 27 should have greater power than occupational studies in manufacturing (Hi:Lo = 9) and office environments (Hi:Lo = 4), especially if exposure is assessed by primary work environment as well as occupation.

This broad survey of ELF-EMF exposures in everyday environments has been possible only by focusing on the GM and P95 of the TWA ELF resultant for MFs and the RMS component perpendicular to the body for EFs. As described in the section "Basic ELF-EMF Concepts," the choice of these metrics is dictated by the exposure assessment methods used by the best epidemiologic studies of ELF-EMF and chronic diseases, such as cancer, cardiovascular disease, and neurodegenerative diseases. However, these choices neglect many other EMF characteristics such as the frequency spectrum, polarization, intermittency, the static MF, MG-MF, and electric shocks that have been linked to health effects by physical, biologic, and epidemiologic research (Kheifets et al. 2009).

Surveying the ELF-EMF environment with only these two metrics is therefore like surveying aquatic life from the ocean's surface with only episodic submarine expeditions into deeper waters. Likewise, instruments such as the Multiwave III that measure ELF-EMFs in their full complexity and models of EMF's impacts on the body have been deployed in only a fraction of the environments in this survey, and never with the thoroughness of the ELF-MF resultant surveys by Zaffanella (1993, 1998). Consequently, our knowledge of the ELF-EMF environment as it affects the human body is somewhat superficial.

A major challenge for the EMF research community is therefore identifying biologically based exposure metrics that are possibly related to chronic diseases and developing instruments that can measure them reliably in large epidemiologic studies. Until better exposure assessment techniques are developed, exposure assessment errors and their biases on risk estimates will probably be present in all ELF-EMF epidemiologic studies, creating uncertainty about their implications for human health.

This chapter's analysis of the present state of ELF-EMF exposure assessment suggests that substantial resources will be required to develop measurement techniques adequate to resolve the questions of cancer and other chronic diseases through epidemiology. However, such investments in better exposure assessments would appear to be justified by the widespread exposures to occupational ELF-MF at levels associated with significant cancer risks (Bowman et al. 2013). As Kheifets et al. (2009) concluded in a recent review, research on improved exposure assessment is a high priority for strengthening ELF-EMF epidemiology so that answers can be found to the stubborn questions about cancer and other chronic diseases.

Acknowledgments

Thoughtful reviews by Chuck Kardous (National Institute for Occupational Safety and Health) and Danielle Vienneau (Swiss Tropical and Public Health Institute) are gratefully acknowledged.

Disclaimer

The findings and conclusions in this chapter are those of the author and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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Epidemiology of **Electromagnetic Fields**

Edited by
Martin Röösli

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Version Date: 20140424

International Standard Book Number-13: 978-1-4665-6817-4 (eBook - PDF)

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Preface

The idea of a possible interaction of magnetism with biological systems is quite old, receiving broad attention for the first time in the eighteenth century when the practice of mesmerism became popular in Europe. Mesmer's treatment is even mentioned in Wolfgang Amadeus Mozart's opera *Così fan tutte*, where, in Scene 4 of Act 1, Despina uses a magnet to treat Ferrando and Guglielmo.

Besides therapeutic applications, modern research began to address possible health risks of magnetic fields in the 1970s. Wertheimer and Leeper (1979) published a study showing an association between electromagnetic field (EMF) exposure (expressed as wire codes; see Chapter 9) with childhood leukemia. Subsequently, most epidemiological research focused on this potential association. The rapid and worldwide increase in wireless communication in the 1990s, however, extended the focus of epidemiological studies to increasingly tackle this type of exposure as well.

Nowadays, the possible health effects of EMFs are a contentious issue among the general public and the scientific community. This debate motivates one aim of this book that is, to summarize a state-of-the-art overview on the scientific evidence. For some, this alone will make this book worthwhile to read. Nevertheless, the scope of this book is much wider, providing an introduction in the methodology of environmental epidemiology for all levels, from student to seasoned researcher.

The first part of the book offers an overview of the general principles and methodological concepts in environmental epidemiology, focusing on EMF examples. Important topics include epidemiological study designs (Chapters 2 and 3), exposure assessment options and implications for the study results (Chapter 4), selection bias (Chapter 5), and confounding and other biases, including reverse causality and ecological fallacy (Chapter 6).

For several reasons, EMF epidemiology is a particularly appealing field within which to explore environmental epidemiological methods in detail. The second part of the book focuses on this theme. First, due to the lack of an established biological mechanism for the interaction of EMFs with the human body in the low-dose range, epidemiological findings are often more critically discussed than in other fields of research. Rigorous sensitivity analysis and simulation studies have been conducted to evaluate the role of bias for observed associations. Some examples are outlined in Chapter 9 for childhood leukemia and exposure to extremely low-frequency magnetic fields and Chapters 12–15 provide examples for brain tumor and mobile phone use. The second reason is the ubiquitous nature of EMFs. Ubiquitously distributed throughout our everyday environment, EMFs originate from numerous sources, ranging from small electrical and communication devices to large infrastructures such as power lines and broadcast transmitters. Detailed information on the range of EMF sources and exposures is presented in Chapters 7 and 8. Also, as presented in Chapter 4, sophisticated exposure assessment methods are often needed to address these varied and often complex exposure situations. Exposure assessment is further complicated by the fact that (1) EMFs cannot be perceived at levels that typically occur in our everyday environment; (2) technical development is very quick, resulting in new and changing exposure scenarios within a short time (Chapter 19); and (3) EMFs interact with the body, making on-body measurements more difficult compared with other environmental exposures. Thus, although modeling of EMF is relatively simple from a physical point of view, researchers are faced with interesting and often impossible challenges in obtaining all the relevant input data for all EMF exposure sources (Chapter 8).

Third, novelty and steep increase of the exposure, in particular for radiofrequency (RF) EMFs from use of wireless communication techniques, are more likely to create inappropriate conception and anxiety in the population. It also results in inherent uncertainties about long-term health effects, particularly given that only a small proportion of the population have used a mobile phone for >20 years, a typical induction period for cancers (Chapters 12–15). This and other challenges have consequences for risk assessment because even relatively small individual risks would have major public health consequences for EMF sources that are used by almost the entire population. Particular examples include mobile and cordless phones and wireless local area network (LAN) as outlined in Chapter 18. In contrast, as illustrated in Chapter 16, false alarms can create economic burden and anxieties in the population that can seriously reduce health-related quality of life.

In the future (Chapter 20), when more is known about the interaction between EMFs and health, it is my hope that this book may also serve as an interesting historical perspective on how the risk assessment of an emerging exposure, with incomplete information and uncertainties, has been dealt with for the benefit of the population.

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Editor

Martin Röösli has a background in atmospheric physics and a PhD in environmental epidemiology. He is a professor at the Swiss Tropical and Public Health Institute in Basel and leads the Unit for Environmental Exposures and Health.

His research focuses on environmental health and includes exposure assessment studies, etiological research, and health risk assessment in the areas of electromagnetic fields, ionizing radiation, noise exposure, passive smoking, climate change, and ambient air pollution.

He has conducted several epidemiological studies on personal exposure and health effects of electromagnetic fields, including occupational studies in railway workers as well as population-based studies dealing with cancer, neurodegenerative diseases, and nonspecific symptoms of ill health. He is a member in various national and international commissions on environmental health risk and has published numerous scientific papers, reviews, and book chapters.

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