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Environmental and Occupationally Encountered Electromagnetic Fields

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CONTENTS

1.1 Introduction

We encounter electromagnetic (EM) fields every day, both naturally occurring and man-made fields. This leads to exposure both in our homes as well as in our various workplaces, and the intensity of the fields varies substantially with the situation. Quite high exposure can occur in some of our occupations as well as our personal activities, for instance, in trains, where the extremely low-frequency (ELF) magnetic field can reach rather high levels. The frequency of the fields we are exposed to covers a wide range, from slowly changing static fields to the gigahertz range.

In this chapter, we give an overview of the fields we encounter in various situations.

1.2 Direct Current and ELF (0–3000 Hz) EM Fields

1.2.1 Naturally Occurring Fields

The most obvious naturally occurring field is the Earth's magnetic field, known since ancient times. The total field intensity diminishes from the poles, with a high of 67 μT at the south magnetic pole and a low of about 30 μT near the equator. In South Brazil, an area with flux densities as low as about 24 μT can be found. Indeed, the angle of the Earth's field to the horizontal (inclination) varies, primarily with latitude, ranging from very small near the equator to almost vertical at high latitudes. More information is available in textbooks (see, e.g., Dubrov [1]) and in databases available on the Web (see, e.g., the U.S. National Geophysical Data Center [2]).

However, the geomagnetic field is not constant, but is continuously subject to more or less strong fluctuations. There are diurnal variations, which may be more pronounced during the day and in summer than at night and in winter (see, e.g., König et al. [3]). There are also short-term variations associated with ionospheric processes. When the solar wind brings protons and electrons toward the Earth, phenomena like the Northern Lights and rapid fluctuations in the geomagnetic field intensity occur. The variation can be rather large; the magnitude of the changes can sometimes be up to 1 μT on a timescale of several minutes. The variation can also be very different in two fairly widely separated places because of the atmospheric conditions. There is also a naturally occurring direct current (DC) electric field at the surface of the Earth in the order of 100–300 V/m (Earth's surface negative) in calm weather and can be 100 kV/m in thunderstorms, caused by atmospheric ions [4].

EM processes associated with lightning discharges are termed as atmospherics or "sferics" in short. They consist mostly of waves in the ELF (strictly speaking 30–300 Hz but usually taken in the bioelectromagnetics literature to extend from 0 to 3000 Hz) and very low-frequency (VLF) ranges (3–30 kHz) (see König et al. [3]). Each second about 100 lightning discharges occur globally, and in the United States one cloud-to-ground flash occurs about every second, averaged over the year [3]. The ELF and VLF signals travel efficiently in the waveguide formed by the Earth and the ionosphere and can be detected many thousands of kilometers from the initiating stroke. Since 1994, several experiments studying the effects of short-term exposure to simulated 10-kHz sferics have been performed at the Department of Clinical and Physiological Psychology at the University of Giessen, Germany [5,6]. In the ELF range, very low-intensity signals, called Schumann resonances, also occur. These are caused by the ionosphere and the Earth's surface acting as a resonant cavity, excited by lightning [3,7] (see also http://www.oulu.fi/~spaceweb/textbook/schumann.html). These cover the low-frequency spectrum, with broad peaks of diminishing amplitude at 7.8, 14, 20, and 26 Hz and higher frequencies. Higher-frequency fields, extending into the microwave region, are also present in atmospheric or intergalactic sources. These fields are much weaker, usually by many

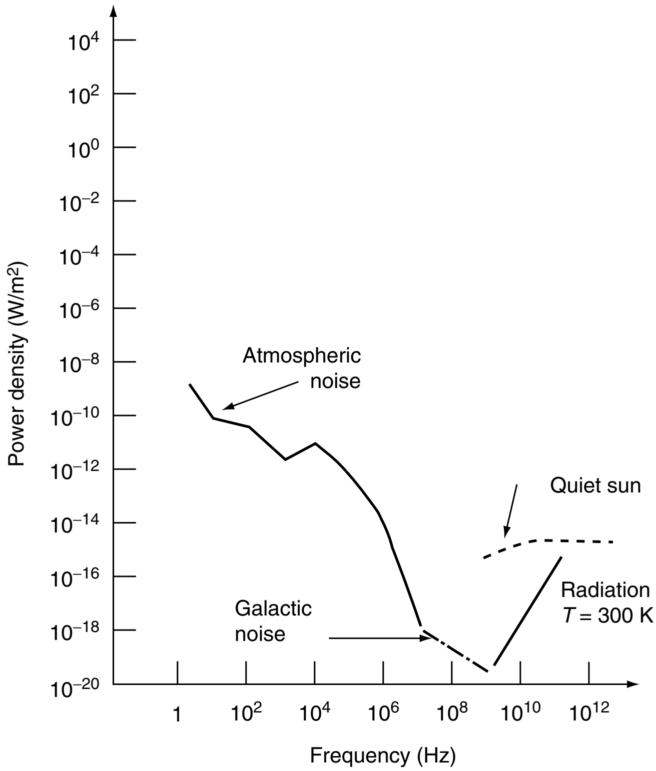

FIGURE 1.1
Power density from natural sources as a function of frequency. (Data from Smith, E. *Proceedings of the IEEE Symposium on Electromagnetic Compatibility*. Institute of Electrical and Electronic Engineering, Piscataway, NJ, 1982. Graph adapted from Barnes, F.S. *Health Phys*. 56, 759–766, 1989. With permission.)

orders of magnitude, than those caused by human activity (compare Figure 1.1 and subsequent tables and figures in this chapter).

1.2.2 Artificial DC and Power Frequency EM Fields in the Environment

1.2.2.1 DC Fields

Although alternate current (AC) power transmission is facilitated by the availability of transformers to change voltages, DC is also useful, especially since high-power, high-efficiency solid-state electronic devices have become available. Overland high-voltage DC lines running at up to ± 1100 kV are found in Europe, North America, and Asia [8] (see also, e.g., http://www.answers.com/topic/high-voltage-direct-current, accessed on August 17, 2005). Electric and magnetic fields near these lines are essentially the same as those for AC lines running at the same voltages and currents, which are discussed below. Because potentials on the cables do not vary in time and there are only two DC conductors (+ and −) instead of the three AC phases, the DC electric fields and space charge clouds of air ions that partially screen them are somewhat different from those near AC transmission lines, though the general features are the same, especially for positions away from the lines. Electric fields, corona, and air ions are discussed further in the AC transmission line section below; see also Refs. [9,10].

For transfer of electric power between countries separated by sea, undersea power cables are especially useful, since their higher capacity causes increased losses in AC.

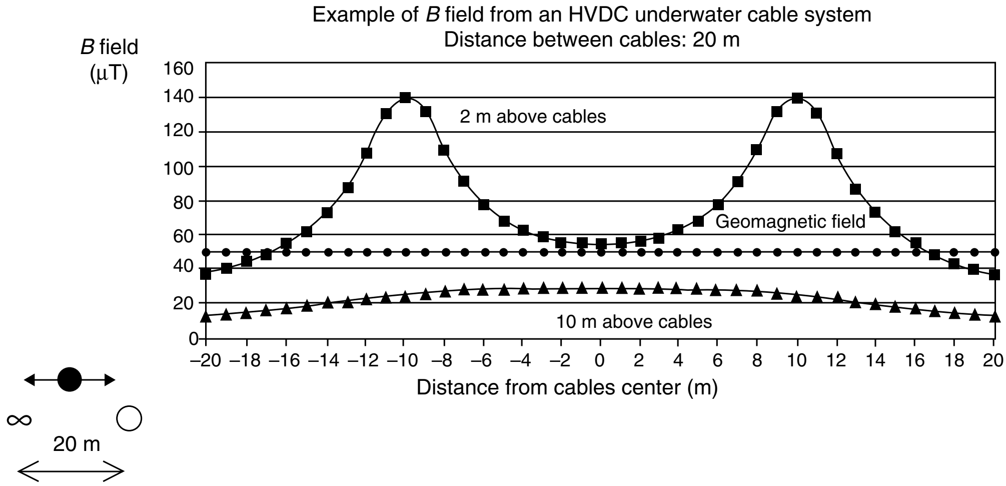

FIGURE 1.2
Predicted DC magnetic field from a high-voltage DC cable with the return cable placed at a distance of 20 m. The current in the cable was assumed to be 1333 A, which is the maximum design current. (From Hansson Mild, K. In Matthes, R., Bernhardt, J.H., and Repacholi, M.H., Eds. Proceedings from a joint seminar, *International Seminar on Effects of Electromagnetic Fields on the Living Environment*, of ICNIRP, WHO, and BfS, Ismaning, Germany, October 4–5, 1999, pp. 21–37. With permission.)

Examples are cables between Sweden and Finland, Denmark, Germany, and Gotland, a Swedish island in the Baltic Sea. Under construction at present is a cable from Sweden to Poland (SwePol). In these cables DC is used, and the ELF component of the current is less than a few tenths of a percent. The maximum current in these cables is slightly above 1000 A, and the estimated normal load is about 30% or 400 A. Depending on the location of the return path, the DC magnetic field will range from a maximum disturbance of the geomagnetic field (with a return through water) to a minimal disturbance (with a return through a second cable as close as possible to the feed cable). With a closest distance of 20 m between the cables, the predicted field distribution can be seen in Figure 1.2, immediately above the cables (2 m), practically the same value as that obtained for a single wire. When the distance between cables is increased beyond 20 m, the distortion at a given distance rises above that of Figure 1.2. Since the cables are shielded, no electric field will be generated outside the cable. For a more detailed discussion of the fields associated with this technique, the reader is referred to the paper by Koops [11].

Few other DC fields from human activity are broadly present in the environment, though very short-range DC fields are found near permanent magnets, usually ranging from a few tenths of a millitesla to a few millitesla at the surface of the magnet and decreasing very rapidly as one moves away. Occupationally encountered DC fields are discussed below.

1.2.2.2 High-Voltage AC Power Lines

The electric and magnetic fields from high-voltage power lines have been figuring for a long time in the debate on the biological effects of EM fields. Although the AC power systems in the Americas, Japan, the island of Taiwan, Korea, and a few other places are 60 Hz, while most of the rest of the world is 50 Hz, the frequency difference has no effect on high-voltage transmission line fields. In the early days of bioelectromagnetics research, the electric field was considered the most important part, and measurements of field strengths were performed in many places. Figure 1.3 shows an example of such

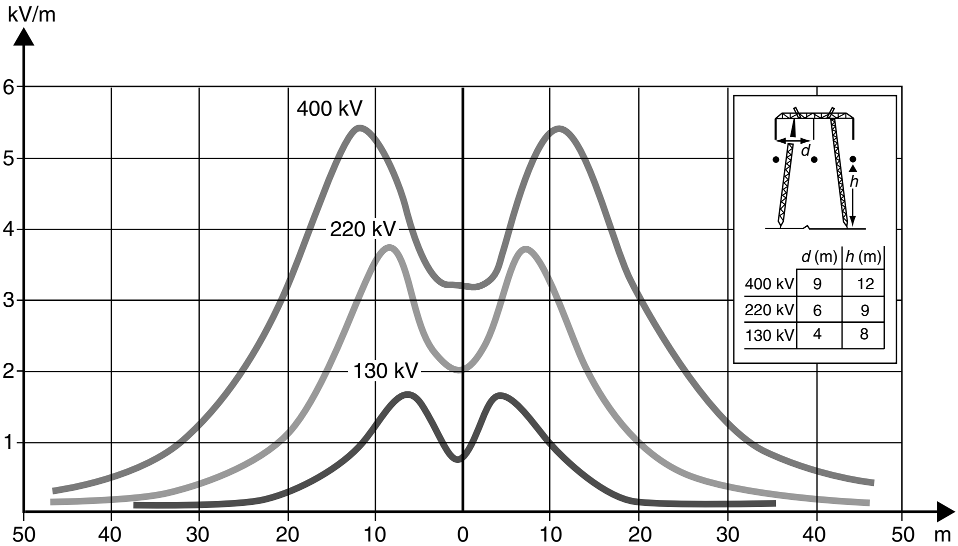

FIGURE 1.3
Electric field from three different high-voltage power lines as a function of the distance from the center of the line. In the inset the distance between the phases as well as the height above ground of the lines are given. (From Hansson Mild, K. In Matthes, R., Bernhardt, J.H., and Repacholi, M.H., Eds. Proceedings from a joint seminar, *International Seminar on Effects of Electromagnetic Fields on the Living Environment*, of ICNIRP, WHO, and BfS, Ismaning, Germany, October 4–5, 1999, pp. 21–37. With permission.)

measurements from three different types of lines: 400, 220, and 130 kV lines, respectively. The field strength depends not only on the voltage of the line but also on the distance between the phases and the height of the tower. The strongest field can be found where the lines are closest to the ground, and this usually occurs midway between two towers. Here, field strengths up to a few kilovolts per meter can be found. Since the guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [12] limit public exposure to 5 kV/m and there is no time averaging for low-frequency fields, people walking under high-voltage power lines may on some occasions be exposed in excess of existing international guidelines.

Because electric fields are well shielded by trees, buildings, or other objects, research in the 1970s and 1980s did not turn up any major health effects (see, e.g., Portier and Wolf [13]), and because of the epidemiological study by Wertheimer and Leeper [14] (see also Chapter 6 on ELF epidemiology in this volume), attention turned from electric to magnetic fields in the environment. The magnetic field from a transmission line or any other wire depends on the current load carried by the line, as well as the distance from the conductors; in Figure 1.4 calculations of the magnetic flux density from several different types of transmission lines are shown. There is a very good agreement between the theoretical calculation and the measured flux density in most situations. The flux density from two-wire power lines is directly proportional to the electric current, generally inversely proportional to the square of the distance to the power line for distances greater than several times the distance between the phase lines, and directly proportional to the distance between the phase wires. For three and six-wire systems the fields decrease more rapidly with distance at a rate that is dependent on the phase sequences and the spacing between the wires. For most lower-voltage lines, around 10–20 kv, the distance at which the B field falls below 0.2 μT is generally less than 10 m; this distance still depends on current and the spacing of the wires.

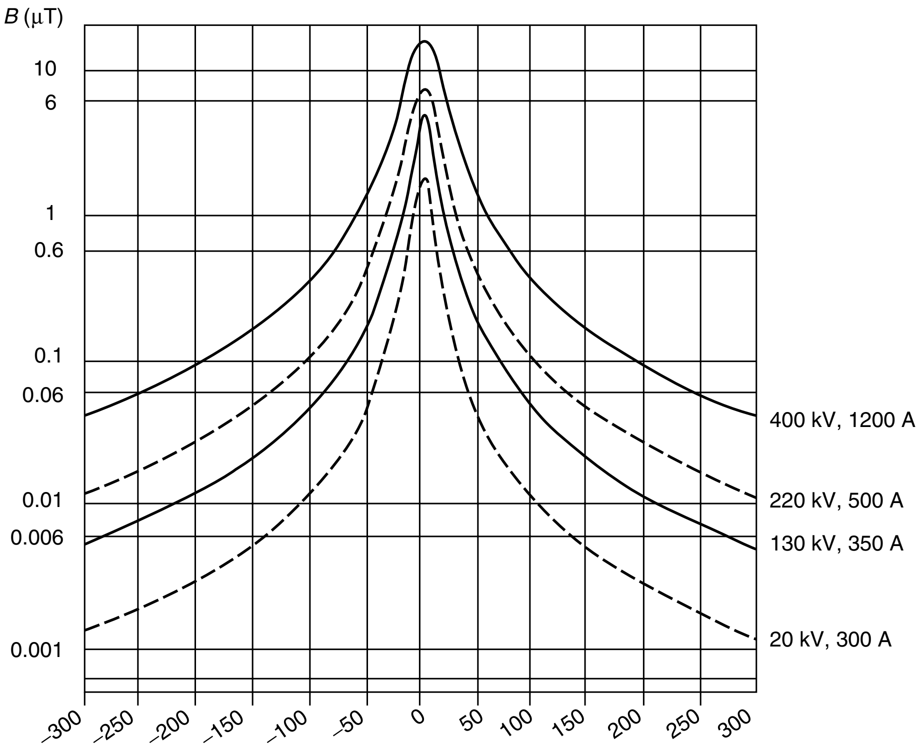

FIGURE 1.4
Magnetic flux density from different high-voltage power lines at a distance (in meters) from the center of the line. The currents in the lines are the maximum values allowed and are given to the right in the figure. (Figure courtesy of Swedish National Institute for Working Life.)

The electric or magnetic field vector from a single AC conductor displays a sinusoidal waveform, oscillating back and forth through zero intensity in a single direction determined by the observation position with respect to the wire, ignoring any small distortions due to harmonics, etc. However, near a three-phase high-voltage transmission line, the electric and magnetic field vectors from the group of conductors, which are at some distance from each other and whose individual sinusoidal variations are out of phase, rotate in space as well as change in magnitude, but their magnitude never decreases exactly to zero [15]. This so-called elliptical polarization may or may not have a different biological significance than the single conductor's ''plane polarization.''

Several approaches have been used for reducing the magnetic field from a line, and in Figure 1.5 some examples are given. Instead of hanging the three phases at the same height and in parallel, the lines can be arranged in a triangular form, thereby reducing the distance between the phases and thus also the flux density. The reduction is of the order of about 1.6. An even greater reduction is obtained if the so-called split phase arrangement is used. Here, five lines are used. One phase is placed in the center, and the other two phases are split into two lines each, which are placed diagonally (see Figure 1.4). The reduction is almost tenfold.

When high voltage is present, there is a possibility of the insulation breaking down, causing a catastrophic discharge—a spark; lightning is an obvious example. There is also the more common possibility of very minor discharges occurring, in which one or a relatively small number of molecules near the high-voltage element become

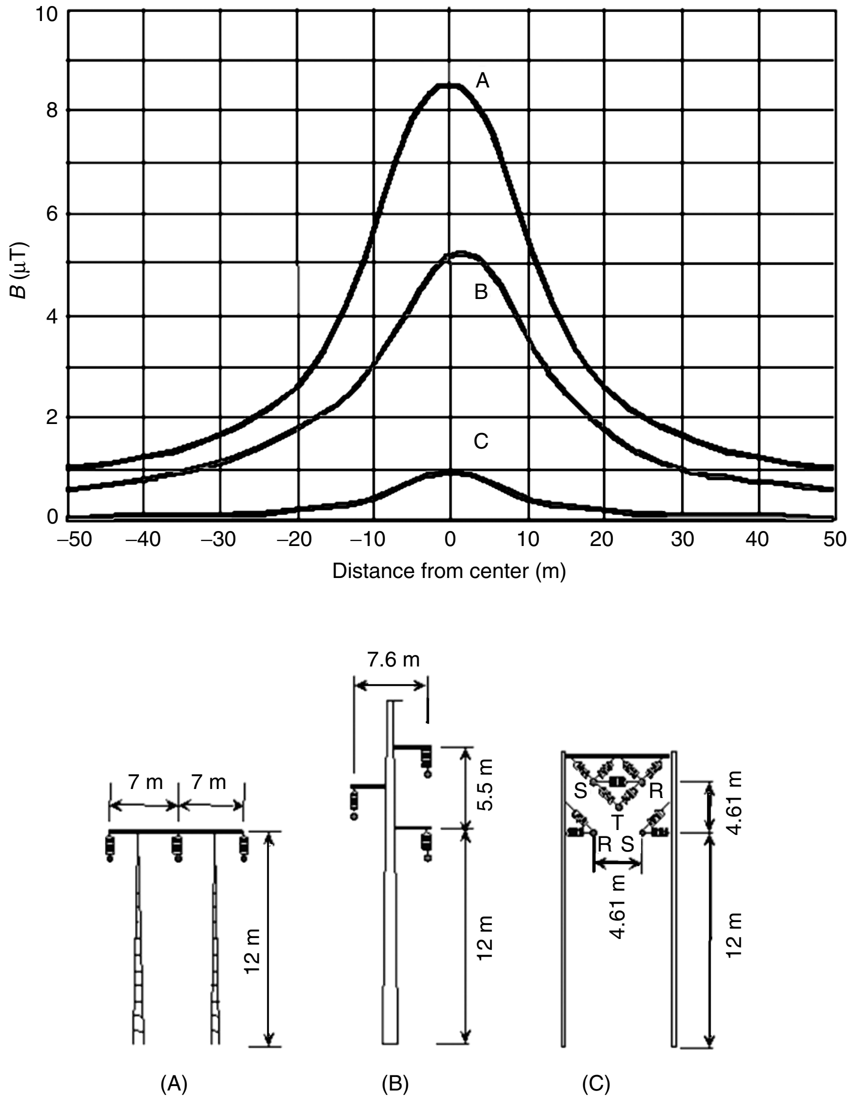

FIGURE 1.5
Examples of reduction of the magnetic flux density from a 220-kV line with a maximum phase current of 500 A. In (A) the normal configuration is used and the maximum flux density is about 8 μT, and in (B) a delta arrangement is used which gives a reduction to about 5 μT maximum under the line. In (C) the split-phase arrangement is used leading to a maximum value of only 1 μT. (Figure courtesy of Swedish National Institute for Working Life.)

ionized; this is often called a *corona*, since in extreme cases a small glow can be seen near parts of the high-voltage system. Corona discharge can also occur at grounded objects near a high voltage and is more likely to occur at more pointed objects; this is the principle of the lightning rod. Minor corona damage has been observed on pine tree needles very close to a 1200 V transmission line [16]. (No other environmental damage to plants or animals from either fields or corona has been found [17].) The resulting ions screen the electric field of the transmission line cables to varying extents, because their number depends on a variety of factors, including humidity, dust, rain, and wind [9,10]. While a hypothesis has been put forward that ions from power lines make small airborne particles, particularly those carrying naturally occurring radioactive atoms, more likely to enter and remain in the lungs and cause cancer or various other diseases [18], it has not found much acceptance.

1.2.2.3 Exposure in Homes

Although Wertheimer and Leeper [14] initially used transmission and distribution line sizes and configurations as surrogates for estimating magnetic field exposure from transmission lines, it quickly became apparent that the correlation was not very good and that sources of exposure inside the home were at least as important, unless the home was very close to a transmission line [13]. Several studies have explored the exposure to ELF electric and magnetic fields in homes in different countries. Deadman et al. [19] investigated the exposure of children in Canada. A logging device was used, which recorded the fields during two consecutive 24-h periods. For 382 children up to the age of 15 they found an arithmetic mean (AM) of the magnetic field of 0.121 μT with a range of 0.01–0.8 μT. The corresponding values for the electric field were AM 14.4 V/m, range 0.82–64.7 V/m. Hansson Mild et al. [20] compared the ELF fields in Swedish and Norwegian residential buildings. The overall mean values were as follows: E fields 54 V/m (SD $=$ 37) and 77 V/m (SD $=$ 58) in Sweden and Norway, respectively; the corresponding values for B fields were 40 nT (SD $=$ 37) and 15 nT (SD $=$ 17). Table 1.1 shows additional comparisons.

Mccurdy et al. [21] measured women's exposure in the United States by using personal magnetic field exposure meters that were worn during a working day or a day at home. The geometric mean of the time-weighted average for the working day was 0.138 μT with a range of 0.022–3.6 μT, and for the homemakers the corresponding values were 0.113 μT, range 0.022–0.403 μT.

In the meta-analysis by Ahlbom et al. [22] on childhood cancer and residential magnetic fields, it was stated that 99.2% of the population resided in homes with $B \leq 0.4$ μT.

Exposure varies widely in time, according to the time of day and the season. One may be outdoors, far from any field sources at one time, indoors near an operating appliance at another, riding in an electric transit vehicle at some other time, and so forth. Sample exposure values for an individual, recorded as a function of time over a 24-h period in spring and summer, are shown in Figure 1.6.

TABLE 1.1

Comparison of Personal Exposure and Background Fields

Country		Geometric Mean of Personal Exposure (nT)	Geometric Mean of Long-Term Background Field (nT)	Ratio, Personal Mean to Background Mean
United States	Adults at home	134	58	2:3
	Adults at home, not in bed	111	74	1:5
	Children, residential	96	99	1:0
	Children, at home	96	67	1:4
Canada	Children at home	117	107	1:1
	Adults at home	133		1:2
U.K.	Adults at home	54	37	1:5
	Adults	42	29	1:5

Source: From Swanson, J. and Kaune, W.T. *Bioelectromagnetics* 20, 244–254, 1999.

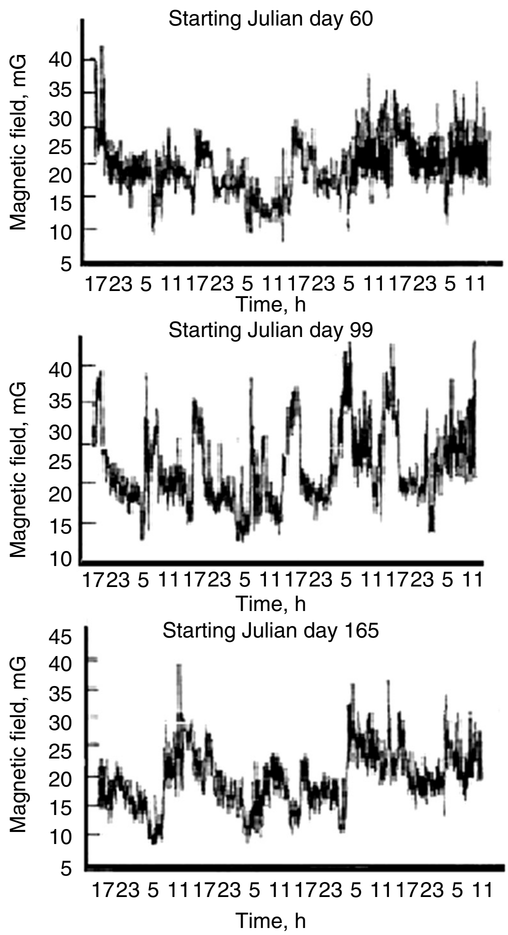

FIGURE 1.6
An individual's measured magnetic field exposure over the course of a day. Note that 1 mG $=$ 0.1 μT. (From Koontz, M.D., Mehegan, L.L., Dietrich, F.M., and Nagda, N.L. Assessment of Children's Long Term Exposure to Magnetic Fields [The Geomet Study]. Final Report TR-101406, Research Project 2966-04, Electric Power Research Institute, Palo Alto, CA, 1992. With permission.)

Since the three-phase systems used for electrical distribution are dimensioned for sinusoidal fields, the harmonic content can create problems. Today we may find large stray currents, usually resulting from unbalanced currents between phases, in water pipes, ventilation systems, concrete reinforcement mesh, etc., and the current flowing also contains these harmonics. Figure 1.7 gives an example of a measurement of a current flowing in a cable in a large apartment building, and Figure 1.8 shows the corresponding Fourier frequency analysis. The magnetic field in the building thus also has these harmonic components. Often, the largest stray currents, which generate large domestic fields, are due to errors in wiring that violate the building code [23] or to a poorly planned wiring layout that has currents flowing in open loops instead of both wires of a circuit being laid next to each other in the same conduit [24].

From Figure 1.6 through Figure 1.8, as well as the data in the rest of this chapter, it is easy to see that average field strength is far from being the only parameter that is needed to characterize electric or magnetic field exposure. Other parameters include frequency or frequencies present (or the related parameters, the rise and fall times of up-and-down excursions or "transients"), numbers and height of transients, number of

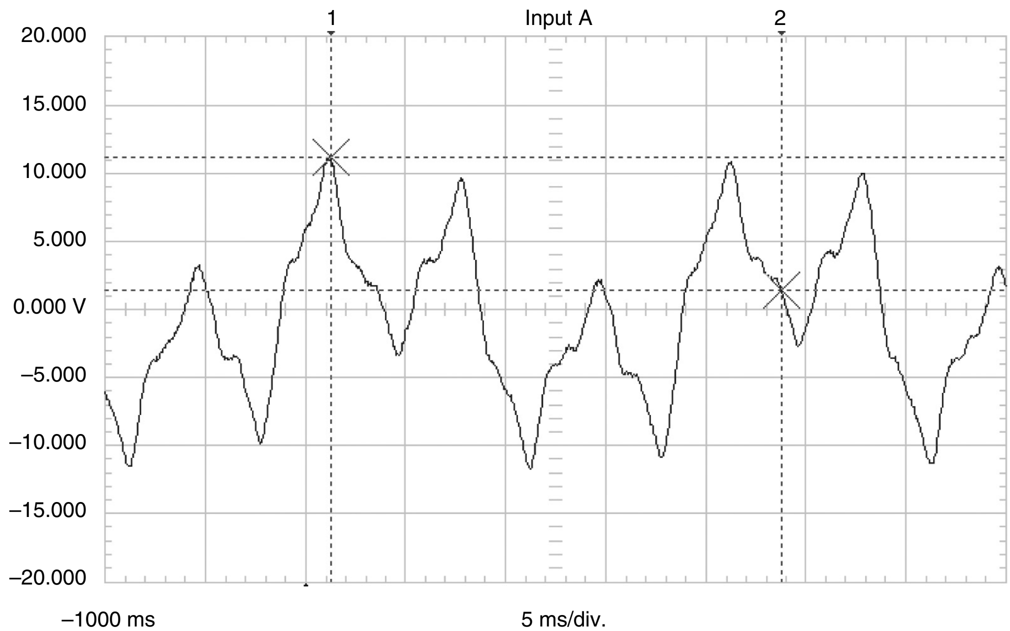

FIGURE 1.7
Stray current wave shape in the 50 Hz power delivery cable in an office building. The peak to peak current is of the order 20 A. (Figure courtesy of Swedish National Institute for Working Life.)

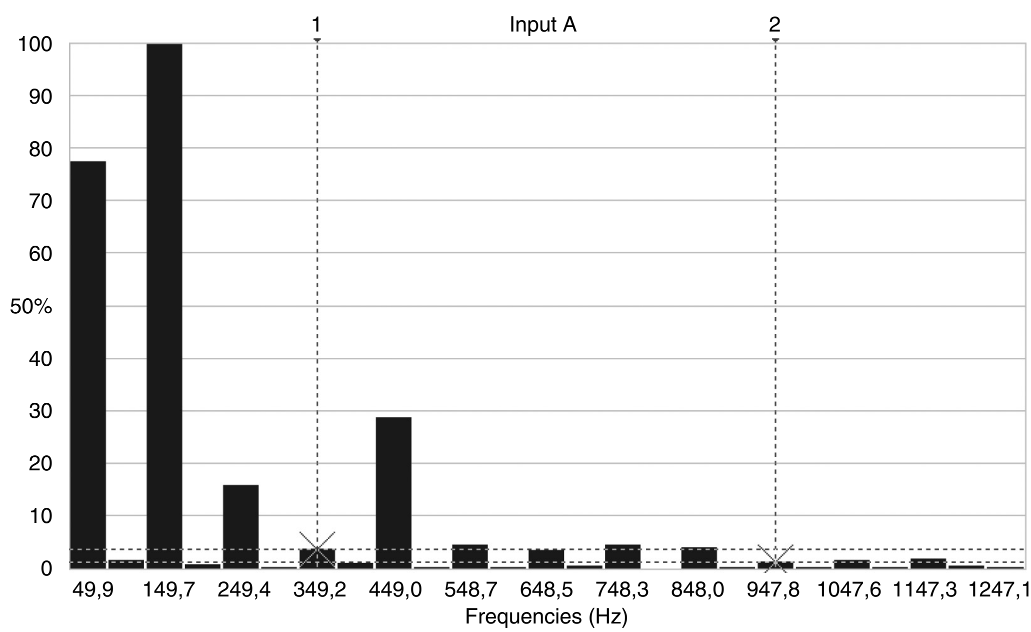

FIGURE 1.8
The Fourier spectrum of the wave shape in Figure 1.5. Note the high 150 Hz (third harmonic) component. (Figure courtesy of Swedish National Institute for Working Life.)

times the field exceeds or falls below a certain fraction of its average value, whether both DC and time-varying fields are present, relative direction of multiple fields, etc. As discussed elsewhere (e.g., the Introduction and chapters such as Chapter 5, Chapter 6, and Chapter 9 in this volume and Chapter 5 through Chapter 8 and Chapter 11 in *BMA*), it is not clear, in most cases, which one or group of these parameters is related to a particular biological effect. To date, average field strength is the most commonly used parameter, partly because it is the most easily obtainable summary of exposure over an extended period. For a given frequency range, average field strength is related to some other parameters, such as fraction of time over a certain threshold, but not to others, such as number of transients per hour. For further discussion of various parameters and their interrelationships, see, for example, Refs. [25,26].

Most measurements have been done in detached houses, even though many city dwellers live in apartment buildings. In apartment buildings, the current in the wiring in the ceiling of one unit, for instance, for ceiling lamps, may most strongly affect the magnetic field level of the unit above. Also, some apartment buildings have an electric substation in the basement, where a transformer reduces the medium-voltage distribution line power to 110 or 220 V for domestic use. The low-voltage conductors of the substation may carry substantial currents and create magnetic fields up to several tens of microtesla directly above the substation; reduction through placing conductors away from the substation ceiling and shielding with aluminum plates is possible [27].

In the United States and Canada, though not in other countries, the neutral wire of the AC power distribution system is required to be physically connected to the earth (grounded) at regular intervals to avoid injury from electric shocks; building wiring systems' neutral wires must also be grounded, often by connection to the buried water pipe as it enters the building. Unbalanced loading of the system can produce currents in the ground system, sometimes including currents that leave one residence through the grounding system and return to the power grid through another, which further contributes to the residential magnetic fields [28,29].

Kavet and colleagues [30–32] have proposed that effects observed in children, which epidemiology has associated with domestic magnetic fields, are in fact due to small shocks that arise due to potential differences that build up between the water tap and the grounded drain of a tub. Shocks received in the bath can still induce in a small child's body current densities of a magnitude known to induce a biological effect. This alternative hypothesis is still under investigation.

1.2.2.4 Electrical Appliances

The United States, Japan, Canada, and some other countries use 110 V_{rms} AC for basic electrical power, while most of the rest of the world uses 230 V. Since transmission and distribution voltages in the two types of system are about the same, only differences due to appliances or building wiring would be expected. For a given power consumption and similar design, 110 V appliances draw twice as much current and create twice as strong a local magnetic field, although their local electric fields are half as strong. However, because both types of field fall off rapidly with increasing distance from the appliance and metal appliance cabinets shield electric fields, measurements of exposure to magnetic fields have not yielded great differences between the two systems (see Table 1.1). Measurements of magnetic fields from a sample of various appliances show that the fields have a rapid falloff with distance from the device [33]. Very close, the values may exceed international guidelines, but at a distance of 0.5–1 m the fields are seldom higher than few tenths of a microtesla. In general, it can be said that the more power the equipment uses, the higher the magnetic field. Table 1.2 presents some representative values from 110 V appliances.

TABLE 1.2

Ratios (B_{on}/B_{off}) of Magnetic Fields Measured with Appliances Turned On and Off

Appliance	Measurement Location	B_{on}/B_{off} 6–54 Hz	54–606	606–3066 Hz	8–200 kHz
Hair dryer	5 cm from nozzle	8.3	57	76	11
	10 cm from nozzle	3.2	17	31	—
	15 cm from nozzle	2.1	7.9	16	—
	25 cm from nozzle	1.4	3.1	6.1	—
Headset playing music	Forehead	1.5	1.0	1.2	—
	Center of head	<1.0	1.0	1.2	1.1
	Above ear	2.0	1.0	2.5	—
	Sternum	1.4	1.0	1.1	—
	Hip	2.7	1.0	2.6	—
Home sewing machines	Front of abdomen	2.7	2.8	2.4	1.5
	Left side of abdomen	1.7	2.0	1.8	—
	Right side of abdomen	1.7	1.6	1.5	—
Motorized clock	10 cm from clock	<1.0	13	4.3	1.1
	25 cm from clock	<1.0	4.0	<1.0	—
	50 cm from clock	<1.0	1.7	<1.0	—
	100 cm from clock	<1.0	1.0	1.0	—
	At subject's head	<1.0	1.4	1.0	—
Electronic clock	10 cm from clock	<1.0	4.7	1.5	1.5
	25 cm from clock	<1.0	1.8	1.0	—
	50 cm from clock	<1.0	1.1	<1.0	—
	100 cm from clock	1.1	1.0	1.0	—
	At subject's head	1.1	1.1	1.0	—

Note: B_{off} was estimated using linear interpolation at those measurement locations where it was not directly measured.

Source: From Kaune, W.T., Miller, M.C., Linet, M.S., Hatch, E.E., Kleinerman, R.A., Wacholder, S., Mohr, A.H., Tarone, R.E., and Haines, C. *Bioelectromagnetics* 23, 14–25, 2002.

Vistnes [34] recently gave some examples of flux densities near 220 V appliances. Of special interest may be a clock radio, which because of bad electrical design may give rise to exposure of the order of 100 μT close to the equipment. Since people are likely to place a clock radio very close to the pillow, the head may be exposed to quite a large magnetic field, exceeding the normal levels in the house.

The general range of magnetic and electric field magnitudes at various distances from transmission lines, local distribution lines, and appliances is shown in Figure 1.9.

Most modern electrical appliances are equipped with an electronically switched power supply in which an electronic circuit replaces the old-style transformer. This means that the current is no longer a pure sinusoidal 50- or 60-Hz signal but contains harmonics. The current used by a low-energy 50-Hz fluorescent lamp is illustrated in Figure 1.10, and the Fourier analysis is shown in Figure 1.11 indicating all the harmonics. Higher harmonics and transients (fast spikelike excursions) are also generated by motor-driven appliances and those run by vibrating mechanisms using make-and-break switching contacts, such as older electric shavers or doorbells (Table 1.2).

The magnetic field in different infant incubators used in hospital nurseries varied between 0.23 and 4.4 μT, with an arithmetic average of 1.0 μT [35]. Most of these values are considerably higher than the exposure that can be measured in residential areas close to transmission lines. The technology to reduce the exposure is at hand and can be easily applied.

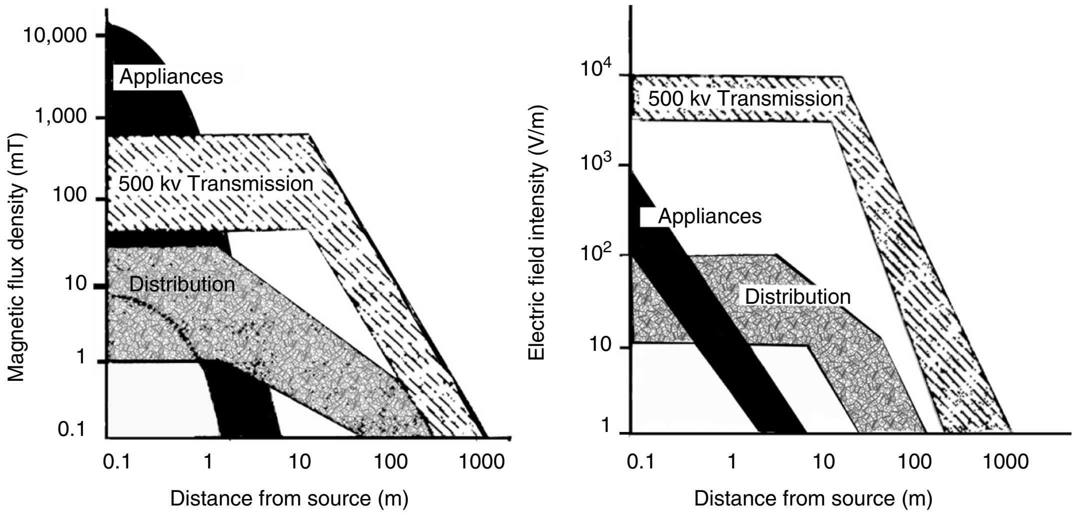

FIGURE 1.9
Magnetic flux density (left) and electric field strength (right) as a function of distance from transmission lines, local distribution lines, and appliances. (From U.S. Office of Technology Assessment. Biological Effects of Power Frequency Electric and Magnetic Fields. U.S. Government Printing Office, Washington, DC, Background Paper OTA-BP-E-53, 1989.)

Occupational exposure from handheld electrical appliances can be quite high. This is mainly equipment that is held close to the body and that uses high power, such as drills and circle saws. These devices usually have adjustable speed, which is done through the switched power supply. Values for the magnetic field of the order 100–200 μT are not uncommon, and in order to show compliance with standards the measurements have to take into account the harmonic contents of the waveform.

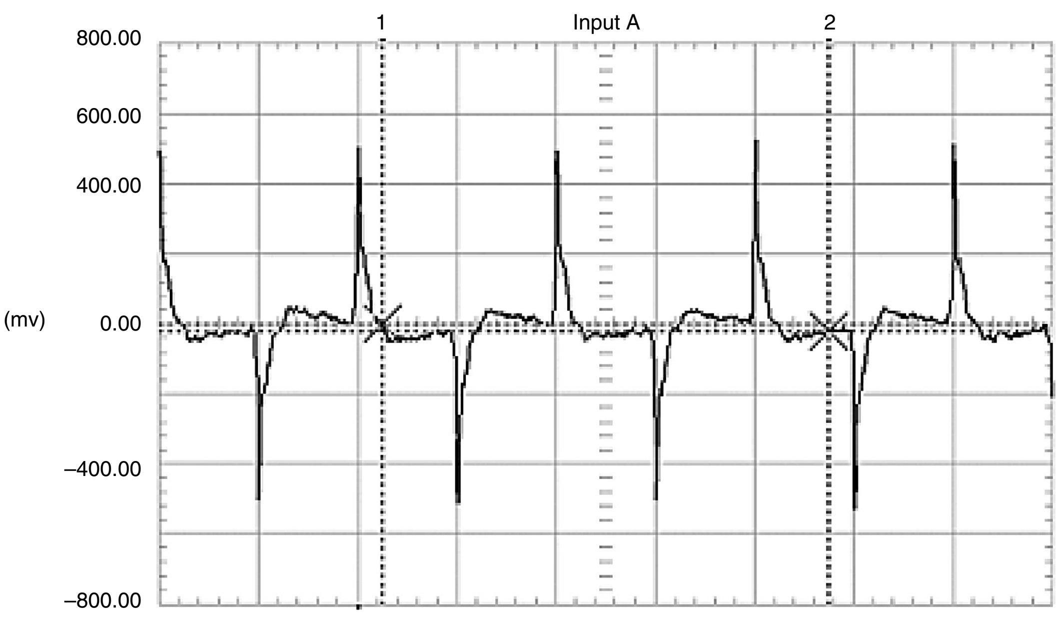

FIGURE 1.10
Wave shape of the current to a low-energy fluorescent lamp. The timescale is 10 ms/div. (Figure courtesy of Swedish National Institute for Working Life.)

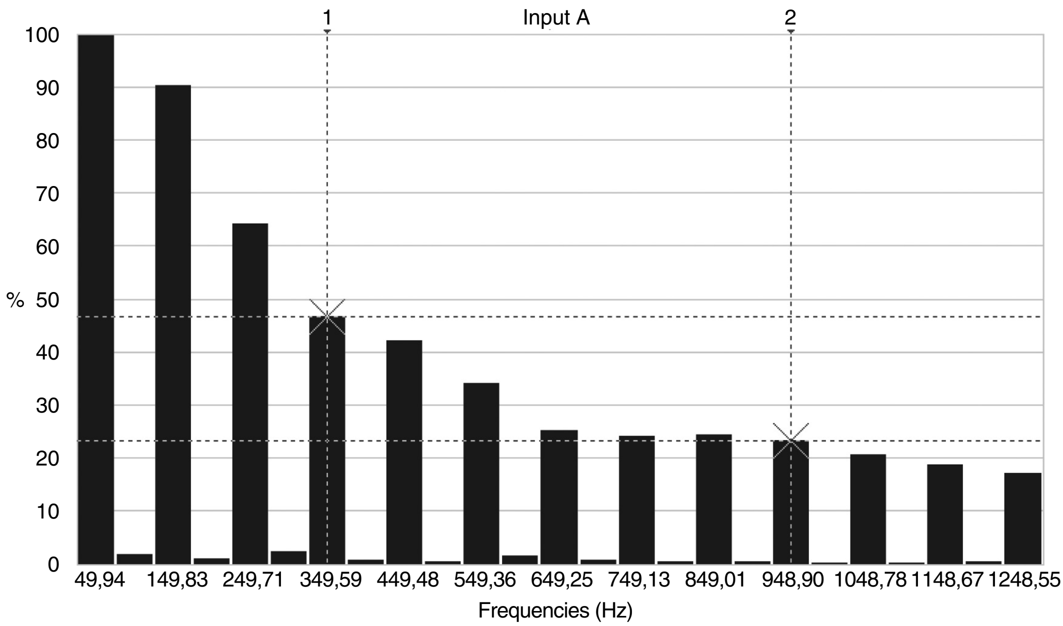

FIGURE 1.11
The Fourier spectrum of the wave shape in Figure 1.7. Note the high 150-Hz component. (Figure courtesy of Swedish National Institute for Working Life.)

1.2.2.5 ELF Fields in Occupational Settings

Wertheimer and Leeper [14] were not only the first to publish evidence in support of increased childhood cancer risk with magnetic field exposure, but they also pointed to increased cancer risk in occupations with high magnetic field exposure. Since then, hundreds of studies have looked into this problem, and the assessment of workers' exposure has been debated. There are studies where individual estimates of the exposure have been made for male [36] and females [37]. For workday means, the 25th, 50th, and 75th percentiles were 0.13, 0.17, and 0.27 μT, respectively, for males, and the corresponding values for females were almost similar: 0.14, 0.17, and 0.23 μT. The study on exposure of males investigated the 1000 most common occupations in Sweden, and the study on female exposure included 61 job categories. Table 1.3 shows additional estimates for various professions.

Sewing machines—Near sewing machines increased magnetic fields can be found, and depending on the type of machines used the values differ. The mean average value logged during some working hours is of the order of several tenths of a microtesla [38].

Welders—Among the occupations where quite high exposure exists, electric arc welders are a prominent example. They handle cables carrying hundreds of amperes very close to their bodies. The welder normally grasps the cable, and it sometimes also is in contact with other parts of the body, for instance, it might be draped over the shoulder. Depending of the technique used—DC or AC, type of rectification, etc.—the ELF magnetic field varies, but several studies report values in the range of tens to hundreds of microtesla [39]. Skotte and Hjøllund [40] found a mean of 21 μT for a full-shift average workday of manual metal arc welders. During the actual welding, the *B* field can be up to several millitesla.

The frequency content of the signal can be rather complex. In one of the most common situations the welding equipment is connected to a three-phase outlet, and the current for the weld is thus three-phase full-wave rectified. This means that we have first a DC

TABLE 1.3

EMF Exposures in Common Environments

Environment	Median[a] Exposure	Top 5th Percentile	Environment	Median[a] Exposure	Top 5th Percentile
Office Building			*Machine Shop*		
Support staff	0.6	3.7	Machinist	0.4	6.0
Professional	0.5	2.6	Welder	1.1	24.6
Maintenance	0.6	3.8	Engineer	1.0	5.1
Visitor	0.6	2.1	Assembler	0.5	6.4000
School			Office staff	0.7	4.7
Teacher	0.6	3.3	*Grocery Store*		
Student	0.5	2.9	Cashier	2.7	11.9
Custodian	1.0	4.9	Butcher	2.4	12.8
Administrative staff	1.3	6.9	Office staff	2.1	7.1
Hospital			Customer	1.1	7.7
Patient	0.6	3.6	—	—	—
Medical staff	0.8	5.6			
Visitor	0.6	2.4			
Maintenance	0.6	5.9			

Note: Magnetic fields are measured in milligauss (mG); 1 mG = 0.1 μT.
[a]The median of four measurements. For this table, the median is the average of the two middle measurements.
Source: National Institute for Occupational Safety and Health. From Portier, C.J. and Wolfe, M.S., Eds. Assessment of Health Effects from Exposure to Power-Line Frequency Electric and Magnetic Fields. NIH Publication 98-3981, National Institute of Health Sciences, Research Triangle Park, NC, 1998 (accessed April. 7, 2005, at http://www.niehs.nih.gov/emfrapid/html/WGReport/WorkingGroup.html).

component and on that a large AC ripple with main frequency 300 Hz (50 Hz power system), but it also has harmonics at 600, 900, 1200 Hz, etc. A newer type of equipment has a pulsed DC (50–200 Hz pulse frequency) as a base with a 53 kHz current applied between the pulses. This leads to frequencies in the current equal to the pulse frequency and its harmonics and also 53 kHz and harmonics. It is a very complex situation to evaluate with respect to compliance with guidelines, because of the complexity of the signal.

Since in many cases, high exposure results from the cables being very close to the body, much can be done to reduce the exposure of the welder by carefully arranging the workstation to keep the cables away from the body. By placing the welding machine on the right-hand side of the worker (if right-handed) and seeing that the return cable is as close as possible to the current cable, the exposure can be reduced by one order of magnitude.

Induction heaters—Induction heating is used for heating metals for purposes that include surface or deep hardening, welding, melting, soft soldering, brazing, annealing, tempering, and relieving stress. The frequency can be from 50 Hz to the low megahertz range, depending on the desired skin depth and purpose. Since high currents are used, the leakage magnetic field can be substantial. At the operator's position, values of the order of 0.5–8 μT are common, and the maximum field near the coil, where, for instance, the hands can be exposed, can reach several hundreds of microtesla. The field strength is in many cases high compared with recommended limits [12].

Railway workers—Engine drivers of AC electric engines experience rather high magnetic field exposure. The intensity depends of several factors, one of them being the age of the engine. Nordensson et al. [41] (see also Refs. [42,43]) found that drivers of Swedish model RC engines were exposed to flux densities of the order of 10–100 μT. The older

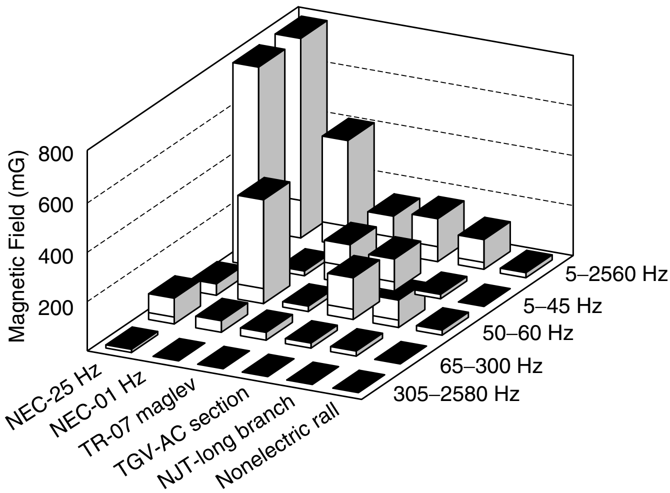

FIGURE 1.12
Maximum (top of bar) and average (horizontal bar) magnetic fields in various frequency bands in the passenger compartment of several intercity rail systems. NEC = U.S. Amtrak Northeast Corridor (Washington, DC, to Boston, MA), which has both 25- and 60-Hz segments; TR-07 = German Transrapid maglev system; TGV = French ''Train a Grande Vitesse,'' AC-powered segment of Paris-Tours line; NJT = New Jersey Transit, NJ Coast Line Long Branch section. (From Bernardi, A., Fraser-Smith, A.C., and Villard, O.G., Jr. *IEEE Trans. Electromagn. Compat*. 31, 413–417, 1989.)

models of engines had the higher values. The mean average values for a full workday ranged from 2 to 15 μT. The main input power frequency is $16\frac{2}{3}$ Hz, and this frequency was dominant at idle, but at full power, harmonics up to 150 Hz existed. Wenzl [44] measured the exposure of rail maintenance workers in the United States and found peak values ranging from 3.4 to 19 μT, and the time-weighted average was in the range 0.3–1.8 μT. Chadwick and Lowes [45] have examined the exposure of passengers on trains in the U.K., and they found static magnetic flux densities up to several microtesla. The alternating field was also substantial in some locations and reached up to 15 mT at floor level. However, none of the whole-body alternating magnetic flux densities approached the National Radiological Protection Board (NRPB) investigation levels.

Trains operating on DC, such as in the Washington, DC, and San Francisco, CA, transit systems, also produce time-varying fields in the passenger compartments, particularly below 5 Hz [46,47]. Figure 1.12 shows field intensity in various frequency bands in the passenger compartment of several representative electric rail systems and a nonelectric one. Interestingly, the figure shows that an experimental magnetic levitation (maglev) system does not exhibit substantially different field levels [48].

Electrochemical plants—In factories producing, for instance, aluminum, copper, or chloride through electrochemical processes, very high DC currents are used, often of the order of tens of kiloamperes. The DC current is obtained through rectification of the incoming three-phase AC power. Often there is still a substantial AC component of the current and hence an AC magnetic field. Measurements have shown broadband ELF measurements of the order of 10–50 μT, with many different frequencies present that need to be taken into account in the evaluation of the exposure situation. Typically, a 50 Hz component can be present, because of unbalance between the three phases, and the full-wave rectification gives 300, 600, and 900 Hz components. The exposure guidelines can often be exceeded in some locations in the plants, and special requirements may be needed to reduce the exposure. DC fields in these smelters are often on the order of several millitesla, with peaks of at least 20–30 mT; up to 70 mT has been reported [49,50].

1.2.2.6 Internal ELF Fields Induced by External and Endogenous Fields

Because the bodies of humans, other animals, and even plants contain ionic solutions and because cell cultures, as well as many one-celled and other organisms such as fish or the roots of plants, live in conductive media, external exposure to electric or time-varying magnetic fields can produce internal fields, which can be quite different than the unperturbed external fields.

In an electric field, as discussed in Chapter 3 and Chapter 4 in this volume on properties of materials, the conductivity and dielectric constants of tissue are quite different from those of air or vacuum, creating a layer of charge due to polarization at the surface of the body, which decreases the internal field, often by many orders of magnitude. For a human standing in the ELF electric field below a high-voltage transmission line, the field inside the body may be only 10^{-6} of the external field. The shape of the body also affects the amount of polarization. Since a standing humans body has more of a ''lightning rod'' shape than a crouching rat, a rat must be exposed to a much lower external field to achieve an equivalent internal electric field. A squatting human will experience lower and the rearing rat, higher fields. The body shape and foot area also affect the average current densities in various body locations because of the external electric field. Figure 1.13 illustrates these differences [51]. As shown in the figure, current densities increase in areas of smaller cross section, for example, the human neck or leg, and closer to the ground, for example, the upper and lower human torso. When calculated without averaging across a cross section, current densities are higher near a junction point; for instance, they are higher and more horizontal at the armpit than in the middle of the chest area [52].

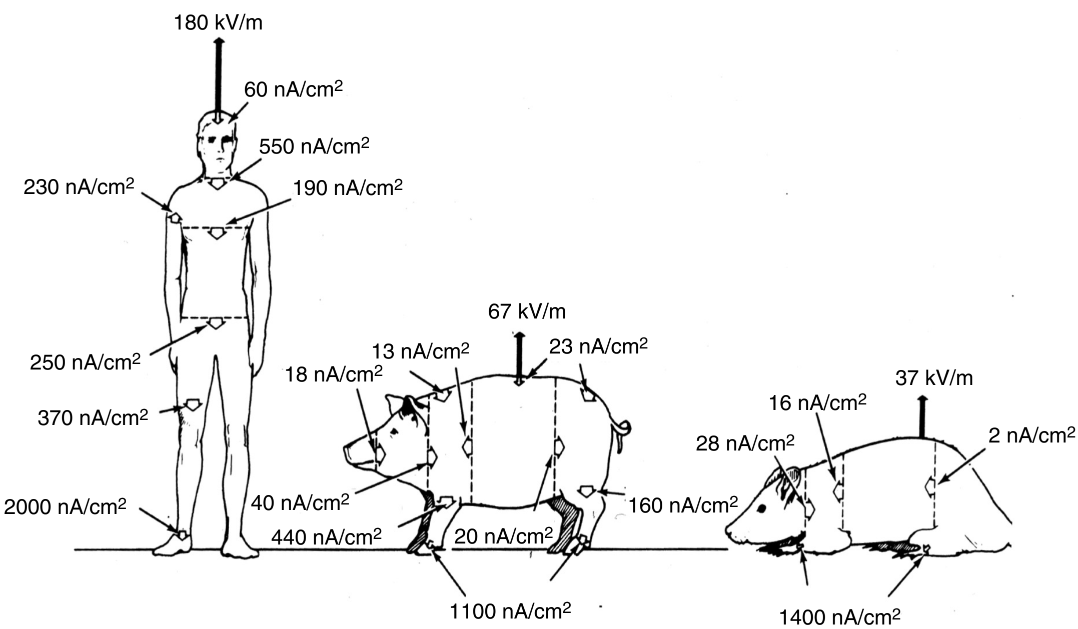

FIGURE 1.13
Estimated external electric field and current densities of a grounded man, pig, and rat exposed to a vertical 0-Hz, 6-kV/m electric field. Calculated internal current densities are averaged over sections through bodies as shown; calculated current densities perpendicular to the body surface are shown for man and pig. (From Figure 4 in Kaune, W.T. and Phillips, R.D. *Bioelectromagnetics* 1, 117–129, 1980; Copyright John Wiley & Sons, reproduced With permission.)

It is important to recognize that electric fields and current densities such as those in Figure 1.13 are averages, whether across the whole cross section of the body or a limb or across a localized region. Fields vary greatly across very small distances when one examines them at dimensions on the order of a cell or a molecule; this is called *micro-dosimetry*. Forming a good picture at this level of fields from either endogenous or external sources is an unsolved but very important problem. Chapter 5 in this volume on basic mechanisms discusses this issue further.

An external magnetic field's value is little changed as it enters a biological system, whether the human body or cells in culture, since the average biological magnetic susceptibilities are very close to those of air or vacuum (see Chapter 3 and Chapter 4 in this volume on magnetic properties of materials). However, the internal electric fields and currents induced in the body according to Faraday's Law are strongly determined by bodys (or specimen) shape, electric conductivity, and orientation with respect to the field. Table 1.4 gives some comparisons between the current induced in a human by the ELF magnetic fields generated in various situations and the external vertical 60 Hz electric field needed to produce the same current densities.

As discussed further in several chapters in this volume, especially Chapter 2 on endogenous fields, Chapter 5 on the basic interactions of fields and biological systems, and Chapter 7 on noise, as well as in the various discussions of models of field–biological system interaction, an externally applied field is unlikely to cause a biological effect unless the part of the biological system with which the field interacts is able to distinguish the external field from the internal electric fields and currents that are an integral part of the system. Exactly how to formulate the aspects of the endogenous field or current

TABLE 1.4

Magnetically Induced Total Body Current and Current Densities and Vertical 60-Hz Electric Field Inducing Equivalent Currents

Source	Current (μA)	Current Density (A/m^2)	Electric Field (kV/m)
Sinusoidal waveforms			
Cord-connected household appliance	20–500	0.5–12[a]	1.5–38
Man in 8-kV/m electric field	120	3[a]	8
Electric blanket (not low field)	7–25	2–40[b]	0.5–1.7
Man in 0.16-kV/m electric field	2.2	0.05[a]	0.16
Nonsinusoidal waveforms—medical devices			
Electric anesthesia device (100-Hz square wave)	10,000	71,000[c]	670
Pacemaker electrode in myocardium[d,e]	6,000	20,000	400
Pacemaker electrode implanted in abdomen[d,f]	6,000	300	400

[a]Through 40-cm^2 ankle.
[b]0.63 cm from electric wire in blanket.
[c]Next to electrode.
[d]Peak pulse current $\sim 10^{-3}$-s duration, repeated every 0.8 s.
[e]Electrode area, 0.3 cm^2.
[f]Electrode area, 20 cm^2.
Source: After Bridges, J.E. and Preache, M. *Proc. IEEE* 69, 1092–1120, 1981. (Slightly modified from Table 1.3, Chapter 2 of second edition.)

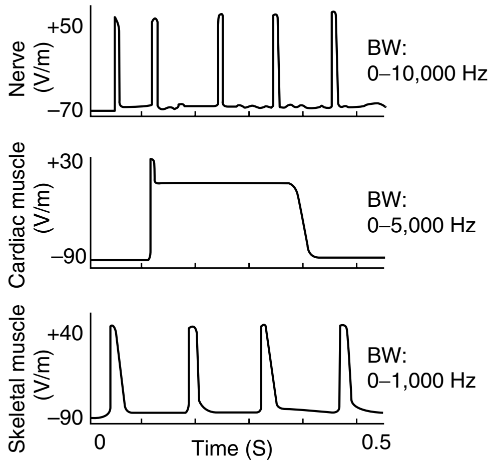

FIGURE 1.14
Typical time course and amplitudes of time-varying membrane potentials (V_m) of various cells. BW is the equivalent frequency bandwidth containing the main Fourier components of each voltage excursion. (From H. Wachtel, University of Colorado, private communication, copyright 1992; reprinted with permission.)

density that should be compared with the local field or currents in a particular situation is still an open research question; for example, over what region (how many molecules or cells) and over what range of frequencies (very narrow or broad) does the biological system average?

These endogenous fields range from the normal ~50–100 mV DC transmembrane potentials of most cells (negative in animals, sometimes positive in plants) to the relatively rapid pulses of nerve cell depolarization or repolarization spikes and the less rapid pulses of, for instance, muscle cells (see Figure 1.14 for examples). They also include the very large and often highly local and hence very nonuniform fields because of local charge densities on some macromolecules or changes in the double ion layer next to a membrane because of the inclusion of a protruding structure, such as a channel, at a particular location (see, e.g., diagrams in Chapter 5 in this volume on basic interactions of fields and biological systems).

1.3 EM Fields at Intermediate and Radio Frequencies (3 kHz to 300 MHz)

1.3.1 Electronic Article Surveillance

Many libraries and stores are currently equipped with electronic article surveillance systems, which generate EM fields ranging from ELF to radio frequencies (RFs). Sometimes, employees spend long periods of time close to parts of these systems, and they might therefore be exposed to strong EM fields, well in excess of the reference levels (RLs). RLs are the levels of easily measured fields in air that exposure-limiting regulations or guidelines state may, but do not necessarily, create health questions in those exposed to them. Above RLs, more precise measurements or calculations are needed for each specific situation to determine whether limits for the actual fields inside the body, the basic restrictions (BRs), are exceeded (for a discussion of RLs and BRs, see Chapter 8 in *BMA*) on standards in [82]).

Kjellsson et al. [53] made measurements on two different systems, one used in a shop and one in a library. The coils in the library at the exit were working at 920 Hz, and the flux density at the center of the coils was of the order of 10 μT, compared with the RL for the general public of 6.25 μT. When the books are returned to the library, the electronic tag in the book has to be activated before the book is put back into the library. The system used for deactivating operates at 50 Hz, and at close range the flux densities were of the order of some millitesla, thus again above the RL for occupational exposure at 500 μT. In the store the signal was a mixture of 17 Hz and 6.25 kHz. The flux densities at the lower frequency were of the order of 200–300 μT, and at the higher frequency the values were well in excess of 100 μT. The RLs at 6.25 kHz for the general public is 6.25 μT, so the RLs are clearly exceeded, and more in-depth analysis is needed to see if the BRs are still not violated. See also Harris et al. [54] for a technical description of these devices.

Both at the shop and in the library there are situations and places where the general public as well as the employees are exposed to magnetic fields that exceed the RL. Logging the exposure during a work shift at the shop also showed that the cashiers are exposed to magnetic fields generated by the transmitter signal of the detection gates, which were often activated by customers during the work shift studied. The cashiers are therefore a highly exposed category of personnel and hence are of interest to include in epidemiological studies. Eskelinen et al. [55] have published similar results and conclusions in a previous study.

In the library not only the detection gates but also the activators and deactivators contribute to the high magnetic fields. One problem is the handheld activator used by the employees. Because of its small size, it is possible to hold the activator against almost every part of the body. If for example, a user is wearing a pacemaker and is not aware of the magnetic fields, the worst case could lead to disturbances in the pacemaker.

1.3.2 EM Fields from Video Display Terminals

A very commonly used appliance emitting EM fields is the computer video display terminal (VDT). Flat panel displays are increasingly replacing the cathode ray tube (CRT)-based VDTs at present, but a great many CRTs are still in use. There are five different types of fields present in the vicinity of the CRT: an electrostatic field, VLF electric and magnetic fields at the horizontal sweep frequencies, and various ELF electric and magnetic fields at the screen refreshing rate, related to the power frequency. These are considered separately in the next few sections. Measurements show that the equivalent electrostatic surface potential on the screen can reach up to 20 kV for some VDTs, and the ELF electric fields in front of the VDT at a distance of 0.5 m range from a few to tens of volts per meter, although most of the time it is not distinguishable from the office background 50 or 60 Hz electric field. The ELF magnetic field can reach a few tenths of a microtesla, and close to the tube the values are up to a few microtesla. The VLF electric fields range from a few to tens of volts per meter, and the corresponding magnetic field is of the order of a few tenths of a microtesla at 0.5 m in front of the VDT. The VLF B field time derivative ranges from a few to a few hundreds of millitesla per second (see Ref. [56]).

In Figure 1.15 a schematic drawing of a CRT-based VDT is shown with the deflection coils. Since these coils are to move the electron beam horizontally, from left to right, the magnetic field affecting the electrons has to be vertically directed; therefore, the coils are in horizontal planes above and below the neck of the tube as shown in Figure 1.15. The stray field from these coils at the operator's position is mainly vertical. The sawtooth wave shape of the magnetic field is also schematically shown in Figure 1.10. The times, 3 and 30 μs, given in the figure are typical examples of values found on some VDTs. Also shown in the figure is the time derivative of the signal. Since the vertical deflection requires a horizontal magnetic field, the coils for the vertical deflection (omitted in the drawing in

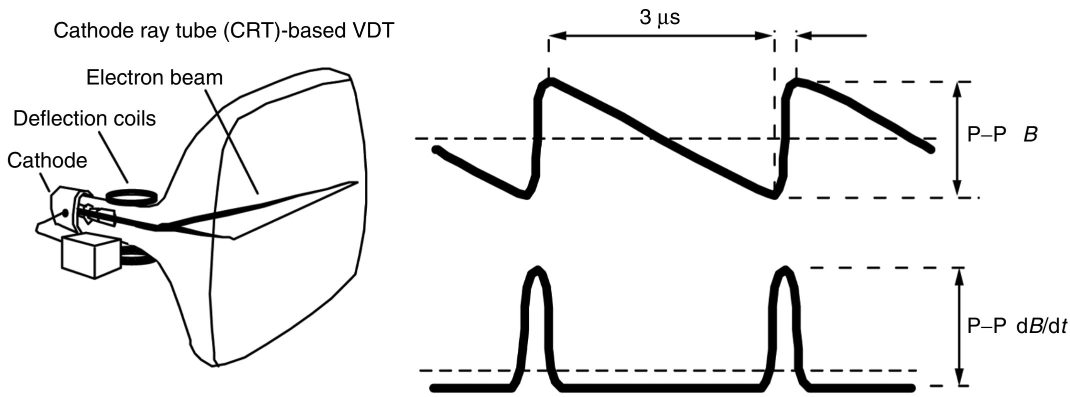

FIGURE 1.15
Schematic drawing of CRT-based VDT. To the right, examples of an idealized waveform of the VLF magnetic field and its time derivative are given. (Figure courtesy of Swedish National Institute for Working Life.)

Figure 1.15) lie in vertical planes on each side of the neck of the tube, giving a horizontal field and, thus, a corresponding stray field. The field from these coils has a frequency equal to the refresh rate, usually equal to or a small harmonic of the line frequency, and has a sawtooth wave shape. The electric field experienced by the operator is usually due to charge accumulating on the screen and is directed between the screen and the operator's body.

The time derivative, dB/dt, is usually measured only for the maximum field component in front of the VDTs. The median values found are 0.63 and 15 mT/s for the ELF and VLF frequency ranges, respectively. The corresponding maximum values are 1.9 and 101 mT/s for the ELF and VLF fields. For the ELF magnetic field in front of the VDT the median value was 0.21 μT. This is then a combination of the general magnetic field level in the office (median value 0.07 μT) and the emission from the VDT [56].

Flat panel displays for computers are presently based primarily on liquid crystal technology, particularly in portable computers. Compared with VDTs they use much lower internal voltages and currents and do not use magnetic field deflection, leading to the presumption that users' exposures are quite low. Even with a flat panel display, it or various sources inside the computer may expose portions of an operator's body to some fields that can approach few tenths of a microtesla in the ELF and VLF regions, especially for a portable computer that is held on the knees. At the time of writing, any values of the fields from laptop computers or other flat panel displays do not seem to have been published in the peer-reviewed literature. Swedish and Australian trade union tests on several laptop computers have shown magnetic field emissions below their internal certification limits for exposure (see Swedish levels in Table 1.5), initially established for VDTs. The Australians found two exceptions: a peak of up to 10 mG for up to 5 s during the program loading and a 0.01–0.16-μT fluctuating field at 30 cm, emanating from the computer transformer (frequencies not given) [57]. Computers with flat panel displays that have ungrounded power supplies, including laptops running either on batteries or on an ungrounded charger, can generate considerable static charges on their screens, producing DC potentials that exceed the Swedish unions' specifications. Older displays using cold-cathode backlighting sometimes also exceed the specifications for ELF or intermediate RF electric fields (Y. Hamnerius, Chalmers University, private communication, 2005).

Computers equipped for local area RF networking, such as ''Wi-Fi'' systems, and hubs for such networks emit and receive fields in the same general ranges of frequency and

TABLE 1.5

Swedish Tjänstemännens Central Organisation (TCO) Certification Limits for Computer Display Terminal Fields

Frequency Band	Quantity	Field Strength	Measurement Distance From Screen
DC	Electric potential	$\pm$0.5 kV	0
Band I	Electric field	$\leq$10 V/m	30 and 50 cm
5 Hz–2 kHz	Magnetic field	$\leq$200 nT	30 and 50 cm
Band II	Electric field	$\leq$1 V/m	30 and 50 cm
20–400 kHz	Magnetic field	$\leq$25 nT	30 and 50 cm

Source: TCO'03 Displays Flat Panel Displays, version 2.01 (translated by Y. Hamnerius), January. 2, 2004 (http://www.tcodevelopment.com).

intensity and are subject to the same sorts of limits as other portable RF devices, such as portable or cell phones. These are discussed later.

CRT-based VDTs use magnetic deflection of the electron beam, and therefore an external magnetic field can cause jitter and flicker on the screen. Sandström et al. [58] applied both 50 and 60 Hz magnetic fields to monitors with different refresh rates. The distortion was detectable from 0.6 up to 1.1 μT for seven monitors investigated. Background magnetic fields higher than 0.5 μT are not uncommon in offices; Sandström et al. [56] found that 5% of the workplaces measured exceeded this value. The ability to detect jitter depends, among other things, on the frequency of the disturbance. Since the frequency of the jitter oscillation is equal to the difference between the frequency of applied magnetic field and the refresh rate, the sensitivity to the external magnetic field will be different with different frequencies of the applied magnetic field.

1.3.3 RF Transmissions

1.3.3.1 Shortwave Transmission

High-power shortwave transmitters (approximately 2–25 MHz) are used for international broadcasts. Often the power supplied to the antenna system can be several hundreds of kilowatts. The antenna systems used are most often movable log-periodic or steerable curtain-type antennas.

Measurements of field strengths from such transmitters have been recently presented by Altpeter et al. [59] in connection with their study on health effects on people living near a station. The magnetic field values ranged from tens of milliamperes per meter for those at a distance of 500 m from the antenna to some tenths of a milliampere per meter for those at a distance of a few kilometers. In a study of leukemia and residence near a high-power shortwave transmitter in Italy, Michelozzi et al. [60] reported spot measurements of the electric field in some of the closest houses to be between 3 and 20 V/m. (Under far-field conditions 3 V/m corresponds to a magnetic field of 8 mA/m and 20 V/m to 53 mA/m.) For a review of measured field strengths see also Mantiply et al. [61].

1.3.3.2 FM Radio and TV Transmission

Exposures to RF fields have been occurring for as long as we have had radio broadcasting. Since the antenna towers are usually quite high and the emissions are directed for reaching a long distance, exposure levels near the towers are minimal. The Environmental Protection Agency has done field strength measurements in the United States, and an

TABLE 1.6

Electric Field Strengths

Source	Distance		
	1 km	**10 km**	**50 km**
(a) Combined electric field strengths from large radio and TV transmitters and one type of base station for mobile phones[a]			
Radio	1	0.1	0.02
UHF TV	5	0.5	0.1
(b) Electric field strengths from radio base stations for Mobile Communication			
	10 m	**100 m**	**1000 m**
Base station	7	0.7	0.07

Note: E field in V/m.

[a]Radio: 60 kW ERP; TV1: 60 kW ERP; TV2: 1000 kW ERP. $S = PG/(4\pi R^2) = E^2/120\pi$. (ERP is the effective radiated power, also expressed as PG, where P is the total power to the antenna and G is the gain; R is the distance to the antenna.)

overview is given by Mantiply et al. [61]. At a distance, the fields can be estimated from calculations using the far-field formula, and some examples are given in Table 1.6. The input power is often highest for UHF TV broadcasting. The TV signal consists of an amplitude-modulated video signal and a frequency-modulated audio signal. In Sweden, for instance, 30 kW of power is used for the video signal and about 5 kW for the audio. With the antenna gain this gives an effective radiated power (ERP) of 1000 kW.

There have not been many radio and TV towers built during the last 10 y or so, although a number have been moved or upgraded, e.g., moved to taller buildings for greater range, but we have seen an increase in the number of terrestrial channels available. New ways of transmitting information have also come into play with digital radio and TV. However, with these the output RF power may be lower; instead, this technique uses a much larger frequency bandwidth.

The total power density of RF exposure of the public has undeniably increased during the last 10 y. Tell and Mantiply [62] reported in 1980 that the average level in the United States from FM radio and TV transmitters was about 50 $\mu W/m^2$. Today, exposure due to such sources is about the same [50], but with mobile phone base stations added, the total power density is now often found to be on the order of 100 $\mu W/m^2$ or so (see Figure 1.16). Despite the proliferation of mobile telephone systems, most of the power is still due to broadcasting (Figure 1.11). Although the total level of RF exposure of the general public has increased during the last few years, it should be clearly stated that at all distances the RF field levels on the ground from base stations are well within the international guidelines for RF exposure of the general public.

1.3.3.3 Wireless Communication Systems (Base Stations, Personal Wireless Devices Such as Cellular Telephones and Pagers)

1.3.3.3.1 Mobile Phone Base Stations

Current mobile telephone systems operate at frequencies between 800 and 2100 MHz, but some older systems operating near 450 MHz are still in use (see Table 1.7). With the rapid increase in the use of mobile phones, the number of base stations has also increased. The phones operate by communicating with a nearby base station, which is a low-powered

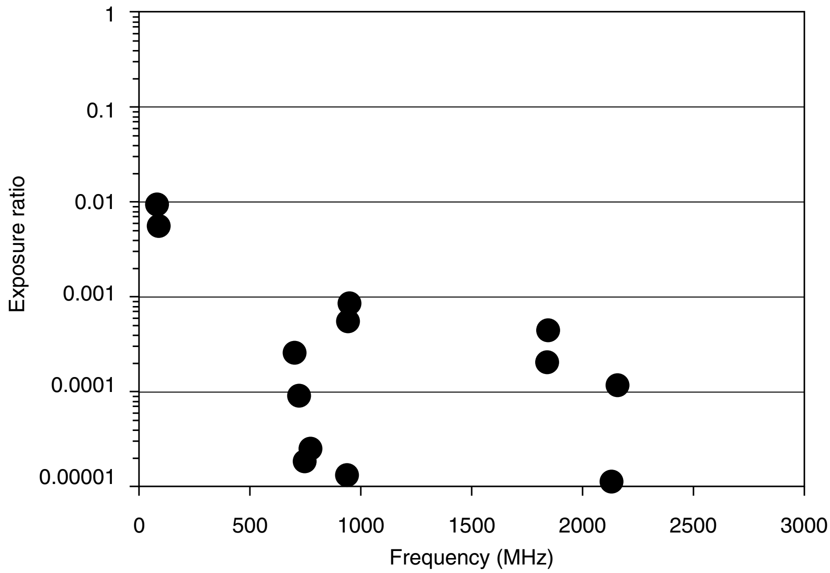

FIGURE 1.16
Power and frequency of environmental RF fields at a sample urban location in Sweden, plotted at each frequency as a comparison to the ICNIRP guideline power limit for personal exposure at the same frequencies, which is set equal to 1 (for plot of limits as a function of frequency, see Chapter 8 in *BMA* on standards in Ref. [82]). (From Hamnerius, Y. COST 281 Workshop 2004/09, Workshop on RF Exposure Assessment, Paris, September 20–21, 2004. With permission.)

radio transmitter, typically mounted on a tower or the roof of a building, that relays calls between the user and the telephone system. In Nordic countries the market penetration is over 100%; that is, there are more mobile phone subscribtions than people; many have more than one phone, and practically everone in the working population has access to a mobile phone. The number of base stations in Sweden is estimated at over 20,000. In 2000,

TABLE 1.7
Frequencies and Modulation Characteristics of Various Mobile Telephone Systems

System	Carrier Frequency	Modulation	Multiplexing Type
TETRA	380–470 MHz	17 Hz	TDMA
MIRS	806–821 MHz	11.1 Hz	TDMA
NADC	824–849 MHz	50 Hz	TDMA
CDMA	824–849 MHz	800 Hz	Multichannel
Analog	824–849 MHz	FM	None
GSM	890–915 MHz	217 Hz	TDMA
PDC	929.2 MHz/1.5 GHz	50 Hz	TDMA
Iridium	1616–1626 MHz	11 Hz	TDMA
CDMA	1765 MHz	800 Hz	Multichannel
PCS	1805–1880 MHz	217 Hz	TDMA
GSM	1800 MHz	217 Hz	TDMA
GSM	1900 MHz	217 Hz	TDMA
NMTS	1920–2170 MHz	100 Hz–1.5 kHz FDD	

Notes: TDMA = Time division multiple access; conversations use different time slices of shared channels. CDMA = code division multiple access; digital identifiers signal phone when the conversation is using one of many closely spaced channels.
Source: Data courtesy of M. Swicord, private communication, 2005.

the United States had more than 82,000 cellular base station sites, some with more than one base station in operation, while there were some 20,000 base stations sites in the U.K. [63].

The antenna system used for base stations comprises often either omnidirectional (whip) antennas, which radiate in all directions in the horizontal plane, or directional (panel) antennas, which radiate energy primarily from their front surfaces. Most commonly employed is a sectorized panel arrangement with three sets of directional transmitting and receiving antennas, oriented 120° apart.

The antennas have a high gain, giving a narrow beam in the vertical direction but a quite wide one in the horizontal direction. In the main beam of the antenna, that is, several meters or more directly in front of and at the same height as the antenna, the intensity of the beam (i.e., the power density) decreases as the inverse square of the distance from it. The RF exposure a person receives from a base station thus depends both on the distance from the antenna and on the angle with respect to the direction of the main beam. At ground level, the signal is relatively weak near the base of the antenna tower since the main beam is passing directly overhead. The ground level signal characteristically increases with distance from the tower to a maximum at between 10 and 100 m from the base of the tower and then decreases at still greater distances. Panel antennas only radiate significant amounts of energy in the forward direction. Thus, for panel antennas mounted facing outward on building parapets, the exposure is low for people on the rooftop or in rooms below the antenna. (See further the 1999 report on cellular telephones and health by the U.K. House of Commons Committee on Science and Technology [64].)

In rural areas, where there is a lower user density, base stations are typically a couple of kilometers apart. In towns and cities where there are more users the cells are smaller and transmitter base stations can be as little as a few hundred meters apart. The actual levels of transmitted power vary widely between urban and rural areas. Since a longer reaching distance is wanted in rural areas, the output power tends to be greater, whereas the large increase in the number and density of base stations within the cities will make the cells smaller and thereby also permit a reduction of output power from the surrounding base stations. Therefore, the levels of public exposure to RF energy from any system will not increase in proportion to the number of its base stations in an area.

In Table 1.6b an example is given of the calculation of electric field strength under far-field conditions. The values given are for the main beam, and since the beam would not be aimed at the ground in the near zone, the theoretical values are presumably overestimating the field strength for close distances. Measurements of field strength from base stations have recently been reported by Thuroczy et al. [65] and Hamnerius and Uddmar [66]. They found levels encountered within about 20 m from the antenna in the range of a few to some tens of volts per meter. However, at distances where most people would be exposed, the field strength is down to tens of millivolts per meter within cities, and in rural area values as low as a few millivolts per meter can be measured. For an estimation of maximum encountered levels, the formula used in Table 1.6b above may be used, and as can be seen from this table values in the range of tens of millivolts per meter are estimated for a distance of 1000 m from the station.

1.3.3.3.2 Handheld Mobile Phones

The technical details of analog and digital systems used for mobile phones have been described in detail [67,68], and only a short background is given here. The Nordic Mobile Telephone (NMT) system operates at 900 MHz with a continuous carrier wave. The maximum output from the handheld NMT900 phones is 1 W. The NMT phones have their output power regulated through the base station in two levels, 0.1 or 1 W; the closer to the station, the lower is the output power likely to be.

To make more efficient use of the available frequencies, various schemes that take advantage of the relatively slow way speech transmits information have allowed more than one conversation to occur in the same frequency channel. Some of these systems include pulsing the RF signal at various frequencies, often in the ELF frequency region, or otherwise modulating it. The result is a departure from a pure, continuous sinusoidal field. In the digital Global System for Mobile Communications (GSM), which is in very common use worldwide, the information is sent in pulses with a repetition rate of 217 Hz. The pulse length and repetition frequency give a duty cycle of 1/8. The maximum output power is 2 W, which gives a time-averaged value of 0.25 W maximum. The GSM system also provides a battery-saving function, which in practice reduces the output power to about half of the maximum. The output power is also regulated from the base station, from a maximum of 2 W down to a minimum of 20 mW, depending on the strength of the signal received at the phone; with the newest phones sold today an even lower value of 5 mW is used. The mean output power is thus normally well below 0.1 W. Frequencies and coding patterns of some other current or proposed mobile telephone signal systems are indicated in Table 1.7.

Different models of phones have different specifications for the antenna design position and physical dimensions, for instance, a dipole antenna or a helical antenna. Kuster [69] measured 16 different European digital phones and found a very wide variation in the SAR values. The phone giving the lowest value, when averaged over time and 10 g of tissue, had a specific absorption rate (SAR) of 0.28 W/kg in the user's head, and the one with the highest value had an SAR of 1.33 W/kg, all normalized to an antenna input power of 0.25 W, which is the maximal value for a GSM phone. If the averaging was done over 1 g of tissue, the span was from a low of 0.42 W/kg to a high of 2.0 W/kg. Anger [70] reported the measurement of SAR on 21 different phones, and his result is similar. The SAR ranged from 0.3 to 1.7 W/kg over 10-g tissues. He also reported the telephone communication power value, that is, how much of the output power can be used for communication, and he found values ranging from only about 5% in the lowest phone to just less than 50% in the "best" phone. Thus, more than half of the output power from the phone is lost because of mismatch between the phone and the antenna, and some is deposited as SAR in the user.

These SAR measurements were done under normal user conditions. However, when the phone is slightly tilted toward the head, Kuster [69] shows that the value can go up from 0.2 to 3.5 W/kg. Thus, for different phones under maximal output, we have a factor of about 5 between the extremes, and to this the personal handling of the phone gives a factor of tenfold or more. It should be noted that all given values are the maximum SAR values found, regardless of the anatomical location. An equal weight is given to the values, independent of whether they are obtained on the external ear, in the middle or inner ear, or behind the ear. In the future, it will be necessary to make the comparison at the same anatomical location. Presumably then, the values as given by Kuster [69] might differ even more.

Taken together there is a rather large uncertainty in estimating the actual SAR that depends on the specific situation, including a factor of 100 from the distance to the base station and at least a factor 10–50 depending on the make and model of the telephone and the personal style of use.

The currents from the battery also give rise to magnetic fields near the phone. For GSM phones magnetic flux densities of a few microtesla near the phone have been measured [66,71]. The fields are pulsed DC fields with a frequency of 217 Hz. For the NMT phones the magnetic field from the battery current can be regarded as pure DC. Jokela et al. [72] recently measured seven different GSM phones and examined the frequency content of the magnetic pulse, and he found that a considerable amount is found in the low kilohertz range. It was even found that some phones exceeded the ICNIRP guideline reference values when the multiple frequency formula was applied, but calculations show that the BRs were not exceeded.

1.3.4 RF EM Fields in Industrial Settings (RF Dielectric Heaters, Worker Exposure to Broadcast Systems)

1.3.4.1 RF Sealers

Operators of RF plastic sealers (RF operators) are an occupational category highly exposed to RF with frequencies around 27 MHz. RFs are used to produce heat to seal, for instance, plastics for tarpaulins, tents, rain clothes, and covers. Around an RF plastic sealer (RF sealer), both a magnetic and an electric field will be present, and close to the machine the coupling between the two is complex since far-field conditions are not at hand.

During RF exposure, a current is induced in the body, the magnitude of which is dependent on many factors such as the electric and magnetic field strength, the polarization of the field, and the grounding conditions. See further Wilén et al. [73], who tested different techniques to measure the induced current in grounded as well as ungrounded conditions.

Within the category of RF sealer operators, many different exposure situations exist, which can roughly be divided into two main types: tarpaulin workers and readymade clothing workers. Tarpaulin workers often stand in front of the RF sealer and will experience whole-body exposure, which often causes a high current to pass through the ankles. Readymade clothing workers often sit down in front of the RF sealer, often without perfect contact with the ground, but with their hands close to the electrode.

To get a good weld, both the welding time and the total power can be adjusted. The combination of the two will produce enough energy to seal the plastic. Typical welding times range from 1 to 10 s, depending on the material being sealed. The total exposure time will also vary between different RF-sealing processes; in the same amount of time, more welds are made in the readymade clothing industry than in the tarpaulin industry. For more information about the welding process see Refs. [74–76].

In a recent study, Wilén et al. [77] studied the exposure among RF sealer operators. The mean values of the calculated 6-min spatially averaged field strengths, in line with ICNIRP recommendations, are 107 V/m and 0.24 A/m, respectively. The maximum measured field strengths were 2 kV/m and 1.5 A/m, respectively. The induced current in ankles varied depending on the work situation, with a mean value of 101 mA and a maximum measured value of 1 A. In total, 16 out of the 46 RF plastic sealers measured exceeded the ICNIRP guidelines.

1.3.4.2 Occupational Exposure from Broadcasting and Radars

Workers in the fields of communication and radar are only exposed to low-level field strength in most situations. However, when climbing FM or TV towers, for instance, accidental exposure can be intense if proper safety precautions are not taken to keep exposure below the regulated limits. The same is true when someone is working near transmitter cabinets with the interlocks defeated and doors open. In these instances, the exposure, usually inadvertent, can be substantial.

Radar is used to detect the presence and directions of aircraft, ships, or other usually movable objects. The systems usually operate in the frequency range from 300 MHz to 15 GHz depending on the purpose of their use. The output power can range from a few milliwatts from police radar to several kilowatts for large air surveillance systems. A short description of various systems can be found, for example, on the WHO Fact Sheet No. 226 [78]. Here, as an example, a short description is given of one usual system where environmental exposure may occur. For civilian air traffic control, radars operating at 1305 MHz are used. The systems use a pulsed field with pulse duration of 2 μs and repetition rate of 625 pps. The peak power is 1.8 MW, and with the antenna gain this gives 3590 MW peak ERP in the maximum direction. Calculations using the far-field formula then give a peak electric field at 5 km of 65 V/m (equivalent power density of 11 W/m^2). However, with the pulsing this comes down to a time-averaged power density of 1.4 $\mu W/cm^2$, and since the antenna is rotating at 9 rpm and the lobe width is 1.2° this is then further reduced to 3×10^{-5} $\mu W/cm^2$. For a review of measurements on different systems see Mantiply et al. [61]

In all known exposure situations of exposure of the general public to EMF from radar systems, the level is below the limiting values given in international guidelines. However, occupational exposure in the near field can occur, and strict adherence to safety instructions is needed, in form of both engineering controls, for example, interlocks, and administrative controls, for instance, strong training and enforcement of safety policies.

1.3.4.3 Exposure in Medical Applications

When medical uses of EM devices are considered, a distinction is made between exposure of patients and medical workers operating the equipment. The balance between any possible risks and the anticipated benefit of exposure of the patient has to be considered by consultation between the patient and the prescribing physician; as a result, exposures are often in excess of limits for workers or the general public. However, operator exposure is governed by the usual rules for occupational exposures; hence, only operator exposure is considered here.

One of the earliest applications of RF energy was shortwave diathermy, which usually operates at 27 MHz. Usually, unshielded electrodes are used, and this may lead to high stray fields. The person operating the equipment, therefore, may be exposed to high field strengths, and the time-averaged guideline for exposure may be exceeded for both RF electric (E) and magnetic (H) fields, depending on the working conditions at hand. Microwave diathermy at 2.45 GHz is also being used in therapy. In this case, the antenna is such that the beam can be directed toward the area to be treated, but the microwave beam may easily be directed toward the patients. Although the beam may not be exposed to the therapist, it may be exposed to the people in the immediate vicinity, including people waiting in the next room. It is therefore necessary to take this into account when planning the space where the microwave diathermy treatment is to be performed.

Electrosurgical units are commonly used in operating suites. They employ RF energy for cutting and coagulation and typically operate at frequencies from about 0.5 MHz to a few megahertz. The energy is supplied to the cutting tool via unshielded cable, which may pass close to the arm and hand of the surgeon, resulting in exposure of operating room personnel to RF energy. The electric and magnetic field near the active lead may be quite high, from a few hundred volts per meter to several kilovolts per meter [79,80]. The induced current in the tissue is of the same order of magnitude as the basic guideline limit for these frequencies, about 5 A/m^2. Since the exposure is rather high, precautionary action would be wise, and shielded wires should be used for the active lead.

Operator and general public exposure to static and RF fields may occur in connection with the use of magnetic resonance imaging (MRI) and nuclear magnetic resonance spectrometers. MRI systems use strong DC magnets, typically from 0.05 to about 3 T, as well as rapidly changing gradient magnetic fields with time derivatives (dB/dt) typically from 1 to 3 mT/ms (1–3 T/s). The RF fields (10–100 MHz) are low and almost fully contained within the patient enclosure, and the RF exposure of the operators is negligible. Inside treatment rooms, near MRI equipment, the maximum exposure level is about 1 T in front of the magnet, and nurses and technicians staying with patients can be exposed to magnetic flux densities up to 200 mT, approaching the protection guideline. When professional activities take place very close to or inside the magnet's tube, workers can be exposed to higher fields (up to 1–2 T), for example, when assisting the patient, plugging in RF cables of treatment coils, or device cleaning. Reduction of the workers' exposure level is possible if MRI device design is required to include operation with workers no less than 0.5 m from the magnet. Workers' training should also include methods for exposure reduction.

Transcranial magnetic stimulation (TMS) has been introduced recently as a noninvasive and focal stimulation tool for the study of connectivity of brain regions, localization of functions, and pathophysiology of neuropsychiatric disorders and a therapeutic intervention method in the treatment of chronic depression. A high-intensity, fast magnetic field pulse produces a cortical stimulus through the induction of locally confined eddy currents; therefore, tailored coil arrangements can be used to achieve controlled local levels of stimulus. The TMS makes use of magnetic fields that can have intensities of up to 1 T with pulse durations in the range of ~0.05 to 0.2 ms. The resulting time derivative of the field can be several tens of kilotesla per second. This impulsive field transient is able to induce a rapid depolarization of the nerve cells within a volume of about 5 mm^3 at the cortical level.

In some instances, the operator holds the TMS transducer coil in place during exposure. Measurements of the leakage magnetic field at different distances from the coils of the transducer show that the intensity of the field decays proportionally to $1/r^3$ (r = distance). The regulations set limits aimed at avoiding excitation of the central nervous system, while TMS or repetitive TMS aims at just reaching the level of local exposure high enough to produce cortical excitations in patients. For the pulse trains in use, one group found a pulse spacing of ~0.3 ms and about 72-μs active pulse width, which gives an equivalent frequency of about 3.5 kHz. For this the limit value is about 1 T/s, and this is transgressed at distances of about 0.7 m from the surface of the transducer's coils under normal treatment conditions [81].

1.4 Conclusion

EM fields, both natural and of human origin, are ubiquitous. Fields of human origin are primarily a result of technological developments that did not begin until late in the 19th century. In general, the natural fields in the environment are much smaller than those inside organisms; natural environmental fields are also usually smaller than fields of human origin at the same frequency. Inside an organism, naturally occurring charges, currents, and fields in cells, tissues, and organs are very important physiologically, and electric charges and magnetic moments are crucial factors in determining molecular structure and chemical reaction rates. Since organisms, including humans, evolved in the natural fields alone, it is not clear how their adaptation to artificial ones might affect them. The other chapters of this handbook explore this question.

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