1. Sources, Exposure and Exposure Assessment

1.1 Sources

1.1.1 *Natural magnetic and electric fields*

Humans are exposed daily to electric and magnetic fields from both natural and man-made sources. The strengths of fields from man-made sources can exceed those from natural sources by several orders of magnitude.

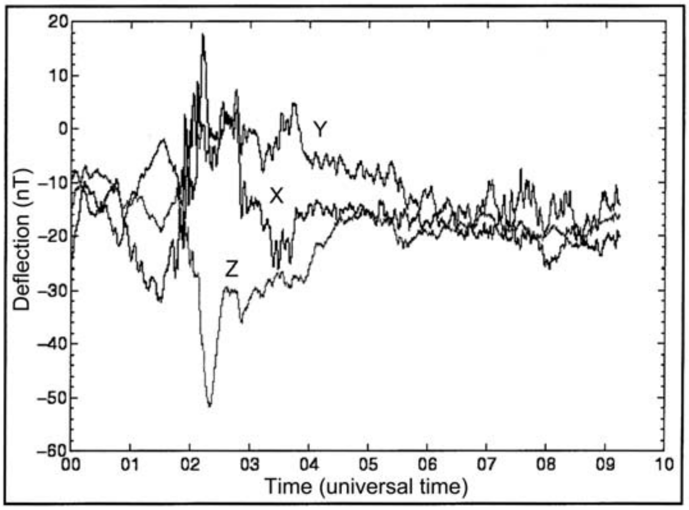
The existence of the geomagnetic field has been known since ancient times. The geomagnetic field is primarily dipolar in nature. The total field intensity diminishes from its maxima of about 60 μT at the magnetic poles, to a minimum of about 30 μT near the equator (König *et al.*, 1981). In temperate latitudes, the geomagnetic field, at sea-level, is approximately 45–50 μT whereas in regions of southern Brazil, flux densities as low as 24 μT have been reported (Hansson Mild, 2000).

The geomagnetic field is not constant but fluctuates continuously and is subject to diurnal, lunar and seasonal variations (Strahler, 1963; König *et al.*, 1981). More information on this subject is available (Dubrov, 1978) and in databases on the Web (e.g. National Geophysical Data Center).

There are also short-term variations associated with ionospheric processes. When the solar wind carries protons and electrons towards the earth, phenomena such as the Northern Lights, and rapid fluctuations in the intensity of the geomagnetic field occur. Figure 1 shows a 9-hour recording made at the Kiruna observatory in Sweden in January 2002. The variation may be large and can sometimes range from 0.1 μT to 1 μT within a few minutes. Such rapid variations are rare and correlated with the solar cycle. More commonly, variations of similar magnitude occur over a longer period of time. Despite these variations, the geomagnetic field should always be considered as a static field.

The atmosphere also has an electric field that is directed radially because the earth is negatively charged. The field strength depends to some extent on geographical latitude; it is lowest towards the poles and the equator and highest in the temperate latitudes. The average strength is around 100 V/m in fair weather, although it may range from 50–500 V/m depending on weather, altitude, time of day and season. During precipitation and bad weather, the values can change considerably, varying over a range of ± 40 000 V/m (König *et al.*, 1981). The average atmospheric electric field is not very different from that produced in most dwellings by typical 50- or 60-Hz electric field

Figure 1. Magnetogram recording from a geomagnetic research station in Kiruna, Sweden



Kiruna magnetogram 2002-01-28, 09:13:35
Real-time geomagnetogram recordings can be seen at (http://www.irf.se/mag). The recordings are made in three axes: X, north, Y, east, and Z, down. The trace shown is the deflection from the mean value of the magnetic field at this location.

power sources (National Radiological Protection Board, 2001), except when measurements are made very close to electric appliances.

The electromagnetic processes associated with lightning discharges are termed *atmospherics* or '*sferics*' for short. They occur in the ELF range and at higher frequencies (König *et al*., 1981). Each second, about 100 lightning discharges occur worldwide and can be detected thousands of kilometres away (Hansson Mild, 2000).

1.1.2 *Man-made fields and exposure*

People are exposed to electric and magnetic fields arising from a wide variety of sources which use electrical energy at various frequencies. Man-made sources are the dominant sources of exposure to time-varying fields. At power frequencies (a term that encompasses 50 and 60 Hz and their harmonics), man-made fields are many thousands of times greater than natural fields arising from either the sun or the earth.

When the source is spatially fixed and the source current and/or electrical potential difference is constant in time, the resulting field is also constant, and is referred to as static, hence the terms *magnetostatic* and *electrostatic*. Electrostatic fields are produced by fixed potential differences. Magnetostatic fields are established by permanent magnets and by steady currents. When the source current or voltage varies in time, for example, in a sinusoidal, pulsed or transient manner, the field varies proportionally.

In practice, the waveform may be a simple sinusoid or may be more complex, indicating the presence of harmonics. Complex waveforms are also observed when transients occur. Transients and interruptions, either in the electric power source or in the load, result in a wide spectrum of frequencies that may extend above several kHz (Portier & Wolfe, 1998).

Power-frequency electric and magnetic fields are ubiquitous and it is important to consider the possibilities of exposure both at work and at home. Epidemiological studies may focus on particular populations because of their proximity to specific sources of exposure, such as local power lines and substations, or because of their use of electrical appliances. These sources of exposure are not necessarily the dominant contributors to a person's time-weighted average exposure if this is indeed the parameter of interest for such studies. Various other metrics have been proposed that reflect aspects of the intermittent and transient characteristics of fields. Man-made sources and their associated fields are discussed more fully elsewhere (see National Radiological Protection Board, 2001).

(*a*) *Residential exposure*

There are three major sources of ELF electric and magnetic fields in homes: multiple grounded current-carrying plumbing and/or electric circuits, appliances and nearby power lines, including lines supplying electricity to individual homes (known as service lines, service drops or drop lines).

(i) *Background exposure*

Extremely low-frequency magnetic fields in homes arise mostly from currents flowing in the distribution circuits, conducting pipes and the electric ground, and from the use of appliances. The magnetic fields are partially cancelled if the load current matches the current returning via the neutral conductor. The cancellation is more effective if the conductors are close together or twisted. In practice, return currents do not flow exclusively through the associated neutral cable, but are able to follow alternative routes because of interconnected neutral cables and multiple earthing of neutral conductors. This diversion of current from the neutral cable associated with a particular phase cable results in unbalanced currents producing a net current that gives rise to a residual magnetic field. These fields produce the general background level inside and outside homes (National Radiological Protection Board, 2001). The magnetic fields in the home that arise from conductive plumbing paths were noted by Wertheimer *et al.* (1995) to "provide opportunity for frequent, prolonged encounters with 'hot spots' of unusually high intensity field — often much higher than the intensity cut-points around [0.2 or 0.3 μT] previously explored".

The background fields in homes have been measured in many studies. Swanson and Kaune (1999) reviewed 27 papers available up to 1997; other significant studies have been reported by Dockerty *et al.* (1998), Zaffanella and Kalton (1998), McBride *et al.* (1999), UK Childhood Cancer Study Investigators (UKCCSI) (1999) and Schüz *et al*. (2000). The distribution of background field intensities in a population is usually best characterized by a log-normal distribution. The mean field varies from country to country, as a consequence of differences in supply voltages, per-capita electricity consumption and wiring practices, particularly those relating to earthing of the neutral. Swanson and Kaune (1999) found that the distribution of background fields, measured over 24 h or longer, in the USA has a geometric mean of 0.06–0.07 μT, corresponding to an arithmetic mean of around 0.11 μT, and that fields in the United Kingdom are lower (geometric mean, 0.036–0.039 μT; arithmetic mean, approximately 0.05 μT), but found insufficient studies to draw firm conclusions on average fields in other European countries. Wiring practices in some countries such as Norway lead to particularly low field strengths in dwellings (Hansson Mild *et al*., 1996).

In addition to average background fields, there is interest in the percentages of homes with fields above various cut-points. Table 1 gives the magnetic field strengths measured over 24 or 48 h in the homes of control subjects from four recent large epidemiological studies of children.

Few homes are exposed to significant fields from high-voltage power lines (see below). Even in homes with fields greater than 0.2 or 0.4 μT, high-voltage power lines are not the commonest source of the field.

The electric field strength measured in the centre of a room is generally in the range 1–20 V/m. Close to domestic appliances and cables, the field strength may increase to a few hundred volts per metre (National Radiological Protection Board, 2001).

Table 1. Measured exposure to magnetic fields in residential epidemiological studies

Study	Country	No. of control children having long-term measurements	Percentage of controls exposed to field strengths greater than	
			0.2 μT	0.4 μT
Linet *et al*. (1997)[a]	USA	530	9.2	0.9
McBride *et al*. (1999)[a]	Canada	304	11.8	3.3
UKCCSI (1999)[a]	United Kingdom	2224	1.5	0.4
Schüz *et al*. (2001a)[b]	Germany	1301	1.4	0.2

UKCCSI, UK Childhood Cancer Study Investigators

[a] Percentages calculated from data on geometric means from Ahlbom *et al*. (2000). (The results presented by Dockerty *et al*. (1999) have not been included as the numbers are too small to be meaningful at these field strengths.)

[b] Percentages calculated from medians from original data. The medians are expected to be very similar to the geometric means.

(ii) *Fields from appliances*

The highest magnetic flux densities to which most people are exposed in the home arise close to domestic appliances that incorporate motors, transformers and heaters (for most people, the highest fields experienced from domestic appliances are also higher than fields experienced at work and outside the home). The flux density decreases rapidly with distance from appliances, varying between the inverse square and inverse cube of distance, and at a distance of 1 m the flux density will usually be similar to background levels. At a distance of 3 cm, magnetic flux densities may be several hundred microtesla or may even approach 2 mT from devices such as hair dryers and can openers, although there can be wide variations in fields at the same distance from similar appliances (National Radiological Protection Board, 2001).

Exposure to magnetic fields from home appliances must be considered separately from exposure to fields due to power lines. Power lines produce relatively low-intensity, small-gradient fields that are always present throughout the home, whereas fields produced by appliances are invariably more intense, have much steeper gradients, and are, for the most part, experienced only sporadically. The appropriate way of combining the two field types into a single measure of exposure depends critically on the exposure metric considered.

Various features of appliances determine their potential to make a significant contribution to the fields to which people are exposed, and epidemiological studies of appliances have focused on particular appliances chosen for the following reasons:

- Use particularly close to or touching the body. Examples include hair dryers, electric shavers, electric drills and saws, and electric can openers or food mixers.
- Use at moderately close distances for extended periods of time. Examples include televisions and video games, sewing machines, bedside clocks and clock radios and night storage heaters, if, for example, they are located close to the bed.
- Use while in bed, combining close proximity with extended periods of use. Examples include electric blankets and water beds (which may or may not be left on overnight).
- Use over a large part of the home. Examples include underfloor electric heating.

Table 2 gives values of broadband magnetic fields at various distances from domestic appliances in use in the United Kingdom (Preece *et al.*, 1997). The magnetic fields were calculated from a mathematical model fitted to actual measurements made on the numbers of appliances shown in the Table. Gauger (1985) and Zaffanella & Kalton (1998) reported narrow band and broadband data, respectively, for the USA. Florig and Hoburg (1990) characterized fields from electric blankets, using a three-dimensional computer model and Wilson *et al.* (1996) used spot measurements made in the home and in the laboratory. They reported that the average magnetic fields to which

Table 2. Resultant broadband magnetic field calculated at 5, 50 and 100 cm from appliances for which valid data could be derived on the basis of measured fields at 5, 30, 60 and 100 cm

	Magnetic field (μT) at discrete distances from the surface of appliances computed from direct measurements						
Appliance type	No.	5 cm	± SD	50 cm	± SD	100 cm	± SD
Television	73	2.69	1.08	0.26	0.11	0.07	0.04
Kettle, electric	49	2.82	1.51	0.05	0.06	0.01	0.02
Video-cassette recorder	42	0.57	0.52	0.06	0.05	0.02	0.02
Vacuum cleaner	42	39.53	74.58	0.78	0.74	0.16	0.12
Hair dryer	39	17.44	15.56	0.12	0.10	0.02	0.02
Microwave oven	34	27.25	16.74	1.66	0.63	0.37	0.14
Washing machine	34	7.73	7.03	0.96	0.56	0.27	0.14
Iron	33	1.84	1.21	0.03	0.02	0.01	0.00
Clock radio	32	2.34	1.96	0.05	0.05	0.01	0.01
Hi-fi system	30	1.56	4.29	0.08	0.14	0.02	0.03
Toaster	29	5.06	2.71	0.09	0.08	0.02	0.02
Central heating boiler	26	7.37	10.10	0.27	0.26	0.06	0.05
Central heating timer	24	5.27	7.05	0.14	0.17	0.03	0.04
Fridge/freezer	23	0.21	0.14	0.05	0.03	0.02	0.01
Radio	23	3.00	3.26	0.06	0.04	0.01	0.01
Central heating pump	21	61.09	59.58	0.51	0.47	0.10	0.10
Cooker	18	2.27	1.33	0.21	0.15	0.06	0.04
Dishwasher	13	5.93	4.99	0.80	0.46	0.23	0.13
Freezer	13	0.42	0.87	0.04	0.02	0.01	0.01
Oven	13	1.79	0.89	0.39	0.23	0.13	0.09
Shower, electric	12	30.82	35.04	0.44	0.75	0.11	0.25
Burglar alarm	10	6.20	5.21	0.18	0.11	0.03	0.02
Food processor	10	12.84	12.84	0.23	0.23	0.04	0.04
Extractor fan	9	45.18	107.96	0.50	0.93	0.08	0.14
Cooker hood	9	4.77	2.53	0.26	0.10	0.06	0.02
Speaker	8	0.48	0.67	0.07	0.13	0.02	0.04
Hand blender	8	76.75	87.09	0.97	1.05	0.15	0.16
Tumble dryer	7	3.93	5.45	0.34	0.42	0.10	0.10
Food mixer	6	69.91	69.91	0.69	0.69	0.11	0.11
Fish-tank pump	6	75.58	64.74	0.32	0.09	0.05	0.01
Computer	6	1.82	1.96	0.14	0.07	0.04	0.02
Electric clock	6	5.00	4.15	0.04	0.00	0.01	0.00
Electric knife	5	27.03	13.88	0.12	0.05	0.02	0.01
Hob	5	2.25	2.57	0.08	0.05	0.01	0.01
Deep-fat fryer	4	4.44	1.99	0.07	0.01	0.01	0.00
Tin/can opener	3	145.70	106.23	1.33	1.33	0.20	0.21
Fluorescent light	3	5.87	8.52	0.15	0.20	0.03	0.03
Fan heater	3	3.64	1.41	0.22	0.18	0.06	0.06
Liquidizer	2	3.28	1.19	0.29	0.35	0.09	0.12

Table 2 (contd)

Appliance type	Magnetic field (μT) at discrete distances from the surface of appliances computed from direct measurements						
	No.	5 cm	± SD	50 cm	± SD	100 cm	± SD
Bottle sterilizer	2	0.41	0.17	0.01	0.00	0.00	0.00
Coffee maker	2	0.57	0.03	0.06	0.07	0.02	0.02
Shaver socket	2	16.60	1.24	0.27	0.01	0.04	0.00
Coffee mill	1	2.47		0.28		0.07	
Shaver, electric	1	164.75		0.84		0.12	
Tape player	1	2.00		0.24		0.06	

From Preece *et al.* (1997)

the whole body is exposed are between 1 and 3 μT. From eight-hour measurements, Lee *et al.* (2000) estimated that the time-weighted average magnetic field exposures from overnight use of electric blankets ranged between 0.1 and 2 μT.

Measurements of personal exposure are expected to be higher than measurements of background fields because they include exposures from sources such as appliances. Swanson and Kaune (1999) found that in seven studies which measured personal exposure and background fields for the same subjects, the ratio varied from 1.0 to 2.3 with an average of 1.4.

(iii) *Power lines*

Power lines operate at voltages ranging from the domestic supply voltage (120 V in North America, 220–240 V in Europe) up to 765 kV in high-voltage power lines (WHO, 1984). At higher voltages, the main source of magnetic field is the load current carried by the line. Higher voltage lines are usually also capable of carrying higher currents. As the voltage of the line and, hence, in general, the current carried, and the separation of the conductors decrease, the load current becomes a progressively less important source of field and the net current, as discussed in (i) above, becomes the dominant source. It is therefore convenient to treat high-voltage power lines (usually taken to mean 100 kV or 132 kV, also referred to as transmission lines) as a separate source of field (Merchant *et al.*, 1994; Swanson, 1999).

High-voltage power lines in different countries follow similar principles, but with differences in detail so that the fields produced are not identical (power-line design as it affects the fields produced was reviewed by Maddock, 1992). For example, high-voltage power lines in the United Kingdom can have lower ground clearances and can carry higher currents than those in some other countries, leading to higher fields under the lines. When power lines carry two or more circuits, there is a choice as to the physical distribution of the various wires on the towers. An arrangement called ‘transposed phasing’, in which the wires or bundles of wire — phases — in the circuit on one side of the tower have the opposite order to those on the other side, results in fields that decrease more rapidly with distance from the lines than the alternatives (Maddock, 1992). Transposed phasing is more common in the United Kingdom than, for example, in the USA.

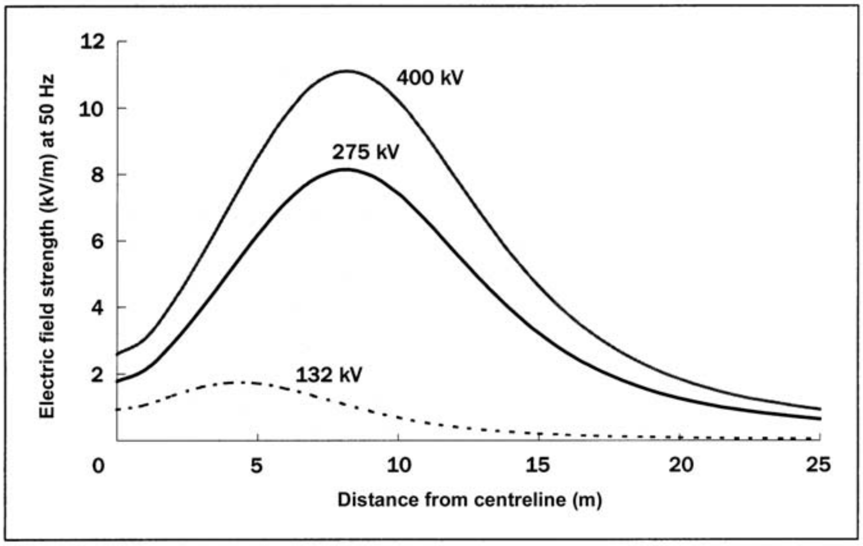
In normal operation, high-voltage power lines have higher ground clearances than the minimum permitted, and carry lower currents than the maximum theoretically possible. Therefore, the fields present in normal operation are substantially lower than the maxima theoretically possible.

Electric fields

High-voltage power lines give rise to the highest electric field strengths that are likely to be encountered by people. The maximum unperturbed electric field strength immediately under 400-kV transmission lines is about 11 kV/m at the minimum clearance of 7.6 m, although people are generally exposed to fields well below this level. Figure 2 gives examples of the variation of electric field strength with distance from the centreline of high-voltage power lines with transposed phasing in the United Kingdom. At 25 m to either side of the line, the field strength is about 1 kV/m (National Radiological Protection Board, 2001).

Objects such as trees and other electrically grounded objects have a screening effect and generally reduce the strength of the electric fields in their vicinity. Buildings attenuate electric fields considerably, and the electric field strength may be one to three

Figure 2. Electric fields from high-voltage overhead power lines



From National Radiological Protection Board (2001) orders of magnitude less inside a building than outside it. Electric fields to which people are exposed inside buildings are generally produced by internal wiring and appliances, and not by external sources (National Radiological Protection Board, 2001).

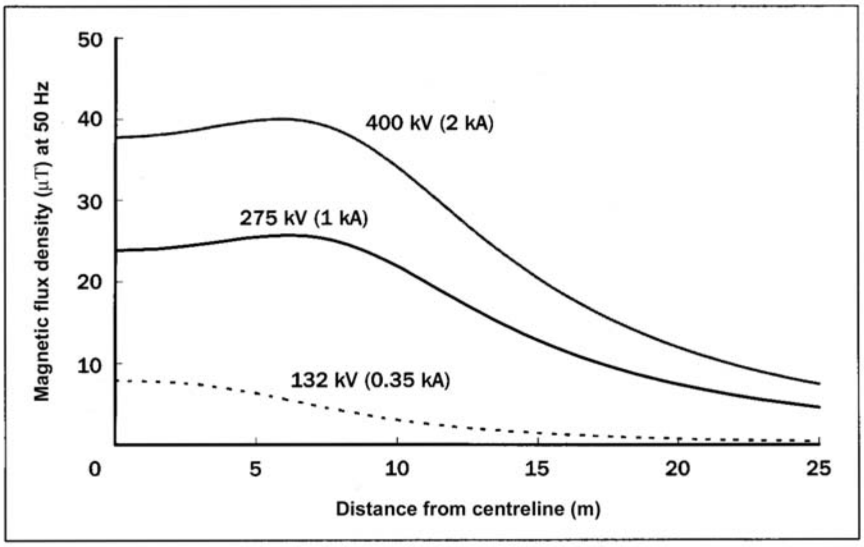
Magnetic fields

The average magnetic flux density measured directly beneath overhead power lines can reach 30 µT for 765-kV lines and 10 µT for the more common 380-kV lines (Repacholi & Greenebaum, 1999). Theoretical calculations of magnetic flux density beneath the highest voltage power line give ranges of up to 100 µT (National Radiological Protection Board, 2001). Figure 3 gives examples of the variation of magnetic flux density with distance from power lines in the United Kingdom. Currents (and hence the fields produced) vary greatly from line to line because power consumption varies with time and according to the area in which it is measured.

Magnetic fields generally fall to background strengths at distances of 50–300 m from high-voltage power lines depending on the line design, current and the strength of background fields in the country concerned (Hansson Mild, 2000). Few people live so close to high-voltage power lines (see Table 3); meaning that these power lines are a major source of exposure for less than 1% of the population according to most studies (see Table 4).

In contrast to electric fields for which the highest exposure is likely to be experienced close to high-voltage power lines, the highest magnetic flux densities are

Figure 3. Magnetic fields from high-voltage overhead power lines



From National Radiological Protection Board (2001)

Table 3. Percentages of people in certain countries within various distances of high-voltage power lines

Country (reference)	No. of subjects	Voltages of power lines included (kV)	Distance (m)	Subjects within this distance	
				No.	%
Canada (McBride *et al.*, 1999)	399[a]	≥ 50	50	4	1.00
			100	7	1.75
Denmark (Olsen *et al.*, 1993)	6495[b]	132–150	75	28	0.43
		50–60	35	22	0.34
					0.46
		50–440	150	52	0.80
United Kingdom (Swanson, 1999)	22 million[c]	≥ 275	50		0.07
			100		0.21
United Kingdom (UKCCSI, 2000a)	3390[a]	≥ 66	50	9	0.27
			120	35	1.03
		≥ 275	50	3	0.09
			120	9	0.27
USA (Kleinerman *et al.*, 2000)	405[a]	≥ 50[d]			
		power line	40	98	24.2
		transmission line	40	20	4.94

UKCCSI, UK Childhood Cancer Study Investigators

[a] Controls from epidemiological study of children

[b] Cases and controls from epidemiological study of children

[c] All homes in England and Wales (Source: Department of Transport, Local Government and the Regions; National Assembly for Wales, 1998, http://www.statistics.gov.uk/statbase/Expodata/Spreadsheets/D4524.xls)

[d] Not stated in Kleinerman *et al.* (2000), assumed to be the same as Wertheimer & Leeper (1979)

more likely to be encountered in the vicinity of appliances or types of equipment that carry large currents (National Radiological Protection Board, 2001).

Direct current lines

Some high-voltage power lines have been designed to carry direct current (DC), therefore producing both electrostatic and magnetostatic fields. Under a 500-kV DC transmission line, the static electric field can reach 30 kV/m or higher, while the magnetostatic field from the line can average 22 μT which adds vectorially to the earth's field (Repacholi & Greenebaum, 1999).

Table 4. Percentages of people in various countries living in homes in which high-voltage power lines produce magnetic fields in excess of specified values

Country (reference)	No. of subjects	Voltages of power lines included (kV)	Measured field (μT)	Subjects whose homes exceed the measured field	
				No.	%
Denmark (Olsen *et al*., 1993)	4788[a]	≥ 50	0.25 0.4	11 3	0.23 0.06
Germany (Schüz *et al*., 2000)	1835[b]	≥ 123	0.2	8	0.44
United Kingdom (UKCCSI, 2000a)	3390[a]	≥ 66[c]	0.2 0.4	11 8	0.32 0.24

UKCCSI, UK Childhood Cancer Study Investigators
[a] Controls from epidemiological study of children
[b] Cases and controls from epidemiological study of children
[c] Probably over 95% were ≥ 132 kV

(iv) *Substations*

Outdoor substations normally do not increase residential exposure to electric and magnetic fields. However, substations inside buildings may result in exposure to magnetic fields at distances less than 5–10 m from the stations (National Radiological Protection Board, 2001). On the floor above a station, flux densities of the order of 10–30 μT may occur depending on the design of the substation (Hansson Mild *et al.*, 1991). Normally, the main sources of field are the electrical connections (known as busbars) between the transformer and the other parts of the substation. The transformer itself can also be a contributory source.

(v) *Exposure to ELF electric and magnetic fields in schools*

Exposure to ELF electric and magnetic fields while at school may represent a significant fraction of a child's total exposure. A study involving 79 schools in Canada took a total of 43 009 measurements of 60-Hz magnetic fields (141–1543 per school). Only 7.8% of all the fields measured were above 0.2 μT. For individual schools, the average magnetic field was 0.08 μT (SD, 0.06 μT). In the analysis by use of room, only typing rooms had magnetic fields that were above 0.2 μT. Hallways and corridors were above 0.1 μT and all other room types were below 0.1 μT. The percentage of classrooms above 0.2 μT was not reported. Magnetic fields above 0.2 μT were mostly associated with wires in the floor or ceiling, proximity to a room containing electrical appliances or movable sources of magnetic fields such as electric typewriters, computers and overhead projectors. Eight of the 79 schools were situated near high-voltage power lines. The survey showed no clear difference in overall magnetic field strength between the schools and domestic environments (Sun *et al.*, 1995).

Kaune *et al.* (1994) measured power-frequency magnetic fields in homes and in the schools and daycare centres of 29 children. Ten public shools, six private schools and one daycare centre were included in the study. In general, the magnetic field strengths measured in schools and daycare centres were smaller and less variable than those measured in residential settings.

The UK Childhood Cancer Study Investigators (UKCCSI) (1999) carried out an epidemiological study of children in which measurements were made in schools as well as homes. Only three of 4452 children aged 0–14 years who spent 15 or more hours per week at school during the winter, had an average exposure during the year above 0.2 μT as a result of exposure at school.

In a preliminary report reviewed elsewhere (Portier & Wolfe, 1998), Neutra *et al.* (1996) reported a median exposure level of 0.08 μT for 163 classrooms at six California schools, with approximately 4% of the classrooms having an average magnetic field in excess of 0.2 μT. These fields were mainly due to ground currents on water pipes, with nearby distribution lines making a smaller contribution. [The Working Group noted that no primary publication was available.] The study was subsequently extended and an executive summary was published in an electronic form, which is available at www.dhs.ca.gov/ehib/emf/school_exp_ass_exec.pdf

(*b*) *Occupational exposure*

Exposure to magnetic fields varies greatly across occupations. The use of personal dosimeters has enabled exposure to be measured for particular types of job. Table 5 (Portier & Wolfe, 1998) lists the time-weighted average exposure to magnetic fields for selected job classifications. In some cases the standard deviations are large. This indicates that there are instances in which workers in these categories are exposed to far stronger fields than the means listed here.

Floderus *et al.* (1993) investigated sets of measurements made at 1015 different workplaces using EMDEX (electric and magnetic field digital exposure system)-100 and EMDEX-C personal dosimeters. This study covered 169 different job categories and participants wore the dosimeters for a mean duration of 6.8 h. The distribution of all 1-s sampling period results for 1015 measurements is shown in Figure 4. The most common measurement was 0.05 μT and measurements above 1 μT were rare. It should be noted that the response of the EMDEX-C is non-linear over a wide frequency range. For example, the railway frequency in Sweden is 16 $^2/_3$ Hz, which means that the measurements obtained with the EMDEX are underestimates of the exposure.

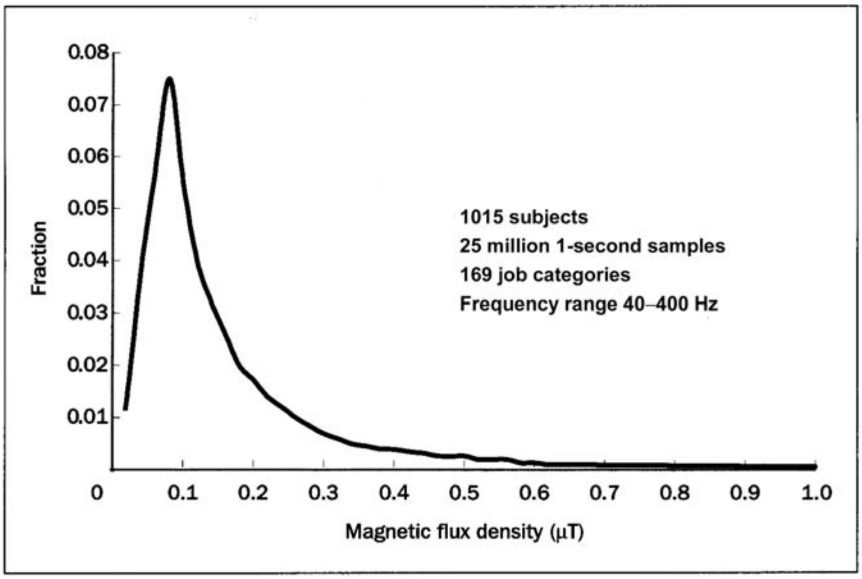
It can be seen from Table 5 that workers in certain occupations are exposed to elevated magnetic fields. Some of the more significant occupations are considered below.

Table 5. Time-weighted average exposure to magnetic fields by job title

Occupational title	Average exposure (μT)	Standard deviation
Train (railroad) driver	4.0	NR
Lineman	3.6	11
Sewing machine user	3.0	0.3
Logging worker	2.5	7.7
Welder	2.0	4.0
Electrician	1.6	1.6
Power station operator	1.4	2.2
Sheet metal worker	1.3	4.2
Cinema projectionist	0.8	0.7

Modified from Portier & Wolfe (1998)
NR, not reported

Figure 4. Distribution of all occupational magnetic field samples



Modified from National Radiological Protection Board (2001) (original figure from Floderus *et al.*, 1993)
The distribution should not be interpreted as a distribution of results for individuals.

(i) *The electric power industry*

Strong magnetic fields are encountered mainly in close proximity to high currents (Maddock, 1992). In the electric power industry, high currents are found in overhead lines and underground cables, and in busbars in power stations and substations. The busbars close to generators in power stations can carry currents up to 20 times higher than those typically carried by the 400-kV transmission system (Merchant *et al.*, 1994).

Exposure to the strong fields produced by these currents can occur either as a direct result of the job, e.g. a lineman or cable splicer, or as a result of work location, e.g. when office workers are located on a power station or substation site. It should be noted that job categories may include workers with very different exposures, e.g. linemen working on live or dead circuits. Therefore, although reporting magnetic-field exposure by job category is useful, a complete understanding of exposure requires a knowledge of the activities or tasks and the location as well as measurements made by personal exposure meters.

The average magnetic fields to which workers are exposed for various jobs in the electric power industry have been reported as follows: 0.18–1.72 μT for workers in power stations, 0.8–1.4 μT for workers in substations, 0.03–4.57 μT for workers on lines and cables and 0.2–18.48 μT for electricians (Portier & Wolfe, 1998; National Radiological Protection Board, 2001).

(ii) *Arc and spot welding*

In arc welding, metal parts are fused together by the energy of a plasma arc struck between two electrodes or between one electrode and the metal to be welded. A power-frequency current usually produces the arc but higher frequencies may be used in addition to strike or to maintain the arc. A feature of arc welding is that the welding cable, which can carry currents of hundreds of amperes, can touch the body of the operator. Stuchly and Lecuyer (1989) surveyed the exposure of arc welders to magnetic fields and determined separately the exposure at 10 cm from the head, chest, waist, gonads, hands and legs. Whilst it is possible for the hand to be exposed to fields in excess of 1 mT, the trunk is typically exposed to several hundred microtesla. Once the arc has been struck, these welders work with comparatively low voltages and this is reflected in the electric field strengths measured; i.e. up to a few tens of volts per metre (National Radiological Protection Board, 2001).

Bowman *et al*. (1988) measured exposure for a tungsten–inert gas welder of up to 90 μT. Similar measurements reported by the National Radiological Protection Board indicate magnetic flux densities of up to 100 μT close to the power supply, 1 mT at the surface of the welding cable and at the surface of the power supply and 100–200 μT at the operator position (National Radiological Protection Board, 2001). London *et al.* (1994) reported the average workday exposure of 22 welders and flame cutters to be much lower (1.95 μT).

(iii) *Induction furnaces*

Measurements on induction furnaces and heaters operating in the frequency range from 50 Hz to 10 kHz have been reported (Lövsund *et al.*, 1982) and are summarized in Table 6. The field strengths decrease rapidly with distance from the coils and do not reflect whole-body exposure. However, in some cases, whole-body exposure occurs. Induction heater operators experience short periods of exposure to relatively strong fields as the induction coils are approached (National Radiological Protection Board, 2001).

Table 6. Frequency and magnetic flux densities from induction furnaces

Type of machine	No.	Frequency band	Magnetic flux density (mT): measured ranges
Ladle furnace in conjunction with 1.6-Hz magnetic stirrer, measurements made at 0.5–1 m from furnace	1	1.6 Hz, 50 Hz	0.2–10
Induction furnace,			
at 0.6–0.9 m	2	50 Hz	0.1–0.9
at 0.8–2.0 m	5	600 Hz	0.1–0.9
Channel furnace, at 0.6–3.0 m	3	50 Hz	0.1–0.4
Induction heater, at 0.1–1.0 m	5	50 Hz–10 kHz	1–60

Modified from Lövsund *et al*. (1982)

(iv) *Electrified transport*

Electricity is utilized in various ways in public transport. The power is supplied as DC or at alternating frequencies up to those used for power distribution. Many European countries such as Austria, Germany, Norway, Sweden and Switzerland have systems that operate at 16 $^2/_3$ Hz. Most of these systems use a DC traction motor, and rectification is carried out either on-board or prior to supply. On-board rectification usually requires a smoothing inductor, a major source of static and 100-Hz alternating magnetic fields. For systems that are supplied with nominal DC there is little smoothing at the rectification stage, resulting in a significant alternating component in the ‘static’ magnetic fields (National Radiological Protection Board, 2001).

On Swedish trains, Nordenson *et al.* (2001) found values ranging from 25 to 120 μT for power-frequency fields in the driver’s cab, depending on the type (age and model) of locomotive. Typical daily average exposures were in the range of 2–15 μT.

Other forms of transport, such as aeroplanes and electrified road vehicles are also expected to increase exposure, but have not been investigated extensively.

(v) *Use of video display terminals*

Occupational exposure to ELF electric and magnetic fields from video display terminals has recently received attention. Video display terminals produce both power-frequency fields and higher frequency fields ranging from about 50 Hz up to 50 kHz (Portier & Wolfe, 1998). Sandström *et al.* (1993) reported median magnetic fields at ELF as 0.21 μT and 0.03 μT for frequencies between 15 kHz and 35 kHz. The median electric fields measured in the same frequency ranges were 20 V/m and 1.5 V/m, respectively.

(vi) *Use of sewing machines*

Hansen *et al.* (2000) reported higher-than-background magnetic fields near industrial sewing machines, because of proximity to motors, with field strengths ranging from 0.32–11.1 μT at a position corresponding approximately to the sternum of the operator. The average exposure for six workers working a full work-shift in the garment industry ranged from 0.21–3.20 μT.

(*c*) *Transients*

Transients occur in electrical systems mainly as a result of switching loads or circuits on and off. They can be produced deliberately, as in circuit testing, or occur accidentally, caused by sudden changes in current load following a short-circuit or lightning strike. Such disturbances invariably have a much higher frequency content than that of the signal that is interrupted (Kaune *et al.*, 2000).

A number of devices have been designed to record electric power transients (Deadman *et al.*, 1988; Héroux, 1991; Kaune *et al.*, 2000). These devices differ primarily in the range of frequencies used to define a transient and in their storage capacities. Kaune *et al.* (2000) examined magnetic transients within the range of 2–200 kHz that had threshold peak intensity levels, measured using a dual channel recorder, of either 3.3 or 33 nT. Recordings were made for a minimum of 24 h in each of 156 homes distributed at six different locations in the USA. Although the recordings of the less intense 3.3-nT transients might have been contaminated somewhat by nearby television sets, this was not the case for the recordings of the 33-nT transients. It was found that transient activity in homes has a distinct diurnal pattern, generally following variations in power use. Evidence was also presented indicating that the occurrence of the larger, 33-nT magnetic transients is increased ($p = 0.01$) in homes with well-grounded metal plumbing that is also electrically connected to an external water system. In contrast, the increased transient activity in the homes tested was not related to wire code.

1.2 Instrumentation and computational methods of assessing electric and magnetic fields

1.2.1 *Instruments*

Measurements of electric and magnetic fields are used to characterize emissions from sources and exposure of persons or experimental subjects. The mechanisms that define internal doses of ELF electric and magnetic fields and relate them to biological effects are not precisely known (Portier & Wolfe, 1998) with the exception of the well-studied neurostimulatory effects of electric and magnetic fields (Bailey *et al.*, 1997; Reilly, 1998). Therefore, it is important that investigators recognize the possible absence of a link between selected measured fields and a biological indicator of dose. The instrument best suited to the purpose of the investigation should be selected carefully. Investigators should evaluate the instrument and its proposed use before starting a study and calibrate it at appropriate intervals thereafter.

Early epidemiological and laboratory studies used simple survey instruments that displayed the maximum field measured along a single axis. More recent studies of magnetic fields have used meters that record the field along three orthogonal axes and report the resultant root-mean-square (rms) field as:

$$\text{Resultant} = \sqrt{(X^2 + Y^2 + Z^2)}$$

Survey meters are easy to use, portable and convenient for measuring field magnitudes over wide areas or in selected locations. Three-axis survey meters are capable of simple signal processing, such as computing the resultant field, storing multiple measurements in their memory or averaging measurements. It is important to note that the resultant field can be equal to, or up to 40% greater (for a circularly polarized field) than, the maximum field measured by a single-axis meter (IEEE, 1995a). Computer-based waveform capture measurement systems are designed to perform sophisticated signal processing and to record signals over periods ranging from a fraction of a second to several days. The instruments discussed here are those most commonly used for measuring fields in the environment or laboratory (Table 7). The measurement capabilities of selected instruments are summarized in Table 8. Less frequently used instruments designed for special purposes are described elsewhere (e.g. WHO, 1984, 1987). The operation of the electric and magnetic field meters recommended for use is described in IEEE (1995a) and IEC (1998).

Table 7. General characteristics of intruments

Meter type	Primary uses	Field parameters measured	Data-collection features	Cost	Ease of use	Data recording	Portability
Computer-based waveform measurement systems	Spot measurements	AC/DC field magnitude (x,y,z, resultant)	Full waveform capture	Very high	High-level technical understanding required	Digitized recording features	Less portable than typical meters
	Mapping	AC field magnitude at each frequency of interest (x,y,z axes, resultant)	Highest quantification content in data collection		The vast quantities of data collected are difficult to manage (approximately 50 kbytes for an average spot measurement vs. 10 bytes with a three-axis AC-field recording meter)		5-kg ‘portable’ system commercially available
	Long-term measurements	AC field polarization					
	Waveform capture	AC–DC orientation					
	Transient capture	Peak-to-peak					
Three-axis AC field recording root-mean-square meter	Personal exposure Spot measurements	AC field magnitude (x,y,z axes, resultant) in a bandwidth dependent upon model	Many have software for mapping capabilities if used with mapping wheel	Medium–high	Almost no instruction required for accurate resultant measurements	Recording features	Small, portable
	Mapping Long-term measurements Exploratory measurements	Some models can provide harmonic content			More difficult to use for exploratory measurements (‘sniffing’) than single-axis meters because of delay between readouts		

Table 7 (contd)

Meter type	Primary uses	Field parameters measured	Data-collection features	Cost	Ease of use	Data recording	Portability
Three-axis cumulative exposure meter with display	Personal exposure Spot measurements Exploratory measurements Long-term measurements for cumulative information	AC field magnitude (x,y,z axes, resultant) in a bandwidth dependent upon model	Most frequently used for personal exposure measurements	Medium	Almost no instruction required for accurate resultant measurements	Records accumulated data, rather than individual samples	Small, portable
Three-axis AC-field survey meter	Spot measurements	AC-field magnitude (x,y,z axes, resultant) in a bandwidth dependent upon model	Similar to three-axis recording meters, with recording capabilities	Medium	Almost no instruction required for accurate resultant measurement	No recording feature	Small, portable
	Exploratory measurements	Some models can provide total harmonic content			More difficult to use for exploratory measurements (‘sniffing’) than single-axis meters because of delay between readouts		
Single-axis AC-field survey meter	Exploratory measurements	AC field magnitude in one direction, in a bandwidth dependent upon model	Can be used to determine polarization	Low	Continuous readout provides easy source investigation	No recording feature	Small, portable
	Spot measurements	Some models can be switched from flat to linear response to provide rough data on presence of harmonics	Easy determination of direction of field Can be used with an audio attachment. For exploratory measurements		Maximum field must be ‘found’ by properly rotating the meter, or measuring in three orthogonal directions to calculate the resultant field		

AC, alternating current; DC, direct current
For further details and handling information, see IEC (1998).

Table 8. Characteristics of field meters

Model	Fields	Sensor	No. of axes	Frequency response (Hz)[a]	Maximum full-scale range (μT)	Output		Function	Comment
AMEX	B	C	1	–	12.5	TWA	AVG	P	
AMEX-3D	B	C	3	25 Hz–1.2 kHz	15	TWA	AVG	P	
EMDEX C	B, E	C, P	3,1	40–400 Hz	2550	D, DL	AVG	P	Built-in E field
EMDEX II	B	C	3	40–800 Hz	300	D, DL	RMS	P	Has harmonic capability
Positron	B, E, HF	C, P, F	3,1	50–60 Hz	50	D, DL	PEAK	P	Built-in E field
Monitor Ind.	B	C	1	40 Hz–1 kHz	250	A	RMS	S	
Multiwave	B	C, FG	3	0–10 kHz	500	D, DL	RMS	S	Waveform capture
Power frequency Meter MOD120	B, E	C, P	1	35–600 Hz	3000	A	AVG	S	
STAR[b]	B	C	3	60 Hz	51	D, DL	RMS	S	
MAG 01	B	FG	1	0–10 Hz	200	D	–	S	
IREQ	B	C	3	40 Hz–1 kHz	100	D, DL	RMS	S	
Field meter	B, E	D	1,1	25 Hz–10 MHz	–	–	–	S	Used by Hietanen & Jokela (1990)
BMM - 3000	B	C	3	5 Hz–2 kHz	2000	A	RMS	S	Frequency filters MPR/TC092 Band I testing
Sydkraft	B	C	1	50–60 Hz	20	D, DL	AVG	S	

Modified from Portier & Wolfe (1998)

E, electric; B, magnetic; HF, high frequency; C, coil, P (sensor), plate; F, conductive foam; FG, flux gate; D (sensor), active dipole; D (output), digital spot; A, analogue spot; DL, data logging; TWA, single readout of TWA; AVG, average; RMS, root-mean-square; P (function), personal monitor; S, survey

[a] Frequency response and maximum range refer only to the magnetic field measurement channel

[b] The specifications are for the original STAR meter that was produced only in limited quantities for non-commercial use. The commercial version of the instrument (Field StAR from Dexsil) has a range of 100 μT on each of three orthogonal axes.

(*a*) *Electric fields*

(i) *Survey meters*

The meters commonly used in occupational and environmental surveys of electric fields are small both for convenience and to minimize their effect on the electric field being measured. To measure the unperturbed field, the meter is suspended at the end of a long non-conductive rod or tripod to minimize interference with the measurement by the investigator. In an oscillating electric field, the current measured between two isolated conducting parts of the sensor is proportional to the field strength. The accuracy of the measurements obtained with these instruments is generally high, except under the following conditions:

- extremes of temperature and humidity;
- insufficient distance of the probe from the investigator;
- instability in meter position;
- loss of non-conductive properties of the supporting rod.

Electric fields can also be measured at fixed locations, e.g. under transmission lines or in laboratory exposure chambers by measuring the current collected by a flat conducting plate placed at ground level. For sinusoidal fields, the electric flux density can be calculated from the area of the plate (A), the permittivity of a vacuum (ε_0), the frequency (f) and the measured current induced in the plate (I_{rms}) in the expression below:

$$E = \frac{I_{rms}}{2\pi f \varepsilon_0 A}$$

Electric field meters can be calibrated by placing the probe in a uniform field produced between two large conducting plates for which the field strength can be easily calculated (IEEE, 1995a, b).

(ii) *Personal exposure meters for measuring electric fields*

Personal exposure meters are instruments for measuring the exposure of a person to electric fields in various environments, e.g. work, home and travel (see below for personal exposure meters for measuring magnetic fields). However, wearing a meter on the body perturbs the electric field being measured in unpredictable ways. Typically, where exposure to electric fields of large groups of subjects is being measured, a meter is placed in an armband, shirt pocket or belt pouch (Male *et al.*, 1987; Bracken, 1993). Perturbation of the ambient field by the body precludes obtaining an absolute value of the field and, at best, the average value of such measurements reflects the relative level of exposure.

(*b*) *Magnetic fields*

(i) *Survey meters*

Magnetic fields can be measured with a survey meter, fixed location monitor or a wearable field meter. The simplest meter measures the voltage induced in a coil of wire. For a sinusoidally varying magnetic field, **B,** of frequency *f*, the voltage, V, induced in the coil is given by:

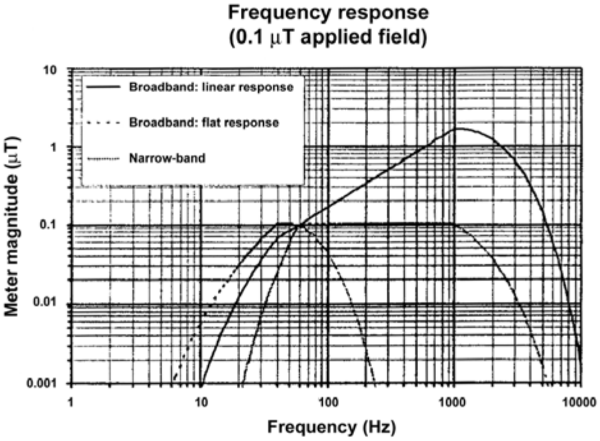
$$V = -2\pi f \mathbf{B_0} A \cos\omega t$$

where *f* is the frequency of the field and $\omega = 2\pi f$, A is the area of the loop, and $\mathbf{B}_0$ is the component of **B** perpendicular to the loop.

The voltage induced by a given field increases with the addition of turns of wire or of a ferromagnetic core. To prevent interference from electric fields, the magnetic field probe must be shielded. If the meter is used for surveys or personal exposure measurements, frequencies lower than approximately 30 Hz must be filtered out to remove voltages induced in the probe by the motion of the meter in the earth's magnetic field.

The presence of higher frequencies, such as harmonics, can affect magnetic field measurements depending on the frequency response of the magnetic field meter. The frequency response of three different meters is illustrated in Figure 5 (modified from Johnson, 1998). These meters are calibrated so that a 60-Hz, 0.1-µT field reads as 0.1 µT on all three instruments. The narrow-band meter focuses on the 60-Hz magnetic field and greatly attenuates the sensitivity of the meter to higher and lower frequencies. The broadband meter provides an accurate measurement of the magnetic field across a wider frequency range because it has a flat frequency response between 40 Hz and 1000 Hz. The broadband meter with a linear response provides very different measurements in this range as the magnetic field reading is weighted by its frequency (Johnson, 1998).

Figure 5. Frequency response of linear broadband, flat broadband and narrow-band magnetic-field meters to a reference field of 0.1 µT



Modified from Johnson (1998)

Fluxgate magnetometers have adequate sensitivity for measuring magnetostatic fields in the range 0.1 μT–0.01 T. Above 100 μT, both AC and DC magnetic fields can be measured using a Hall effect sensor (IEEE, 1995b). The sensor is designed to measure the voltage across a thin strip of semiconducting material carrying a control current. The voltage change is directly related to the magnetic flux density of AC and DC magnetic fields (Agnew, 1992).

Early survey meters made average field readings and then extrapolated them to root-mean-square values by applying a calibration factor. These meters give erroneous readings when in the presence of harmonics and complex waveforms.

(ii) *Personal exposure meters for measuring magnetic fields*

Wearable meters for measuring magnetic fields have facilitated assessments of the personal exposure of individuals as they go about daily activities at home, school and work. A few instruments can also record electric-field measurements. The available personal exposure meters can integrate field readings in single or multiple data registers over the course of a measurement period. For a single-channel device, the result is a single value representing the integrated exposure over time in μT·h or (kV/m) h. Some meters classify and accumulate exposures into defined intensity ‘bins’. Other personal exposure meters collect samples at fixed intervals and store the measurements in computer memory for subsequent downloading and analysis (see Table 9).

One of the most popular instruments used in occupational surveys and epidemiological studies is the electric and magnetic field digital exposure system (EMDEX). The EMDEX II data logger records the analogue output from three orthogonal coils or the computed resultant magnetic field. It can also record the electric field detected by a separate sensor. Different versions of the meter are used for environmental field ranges (0.01 μT–0.3 mT) and near high intensity sources (0.4 μT–12 mT) (data from the manufacturer, 2001).

Smaller, lighter versions of the EMDEX are available to collect time series records over longer time periods (EMDEX Lite) or to provide statistical descriptors — mean, standard deviation, minimum, maximum and accumulated time above specified thresholds — of accumulated measurements (EMDEX Mate). The AMEX (average magnetic exposure)-3D measures only the average magnetic field over time of use. IEC (1998) has provided detailed recommendations for the use of instruments in measuring personal exposure to magnetic fields.

(iii) *Frequency response*

The bandwidth of magnetic field meters is generally between 40 Hz and 1000 Hz. Further differentiation of field frequency within this range is not possible unless filtered to a narrow frequency band of 50 or 60 Hz. However, a data logger, the SPECLITE®, was employed in one study to record the magnetic field in 30 frequency bins within this range at 1-min intervals (Philips *et al.*, 1995).

Table 9. Commercially available instruments for measuring ELF magnetic fields[a]

Company, location	**Meter, field type**	**Frequency range**
AlphaLab Inc. Salt Lake City, Utah, USA	TriField Meter (3-axis **E**, **M** & **RF**)	50 Hz–3 GHz
Bartington Instruments Ltd Oxford, England	MAG-01 (1-axis **M**)	DC–a few kHz
	MAG-03 (3-axis **M**)	0 Hz–3000 Hz
Combinova AB Bromma, Sweden	MFM 10 (3-axis **M** recording)	20 Hz–2000 Hz
	MFM 1020 (3-axis **E**, **M** recording)	5 Hz–400 kHz
	FD 1 (**E**, 3-axis **M** survey)	20 Hz–2000 Hz
	FD 3 (3-axis **M** recording)	20 Hz–2000 Hz
Dexsil Corp. Hamden, Connecticut, USA	Field Star 1000 (3-axis **M** recording)	not specified
	Field Star 4000 (3-axis **M** recording)	not specified
	Magnum 310 (3-axis **M** survey)	40 Hz–310 Hz
Electric Research Pittsburgh, Pennsylvania, USA	MultiWave® System II (**E**, **M** 3-axis, waveform)	0–3000 Hz
Enertech Consultants Campbell, California, USA	EMDEX SNAP (3-axis **M** survey)	40 Hz–1000 Hz
	EMDEX PAL (3-axis **M** limited recording)	40 Hz–1000 Hz
	EMDEX MATE (3-axis **M** limited recording)	40 Hz–1000 Hz
	EMDEX LITE (3-axis **M** recording)	10 Hz–1000 Hz
	EMDEX II (3-axis **E** & **M** recording)	40 Hz–800 Hz
	EMDEX WaveCorder (3-axis **M** waveform)	10 Hz–3000 Hz
	EMDEX Transient Counter (3-axis **M**)	2000 Hz–220 000 Hz
EnviroMentor AB Mölndal, Sweden	Field Finder Lite (1-axis **M** & **E**)	15 Hz–1500 Hz
	Field Finder (3-axis **M** & 1-axis **E**)	30 Hz–2000 Hz
	ML-1 (3-axis **M,** 3-dimensional presentation)	30 Hz–2000 Hz
	BMM-3000 (3-axis **M**, analysis program)	5 Hz–2000 Hz
Holaday Industries, Inc. Eden Prairie, Minnesota, USA	HI-3624 (**M**)	30 Hz–2000 Hz
	HI-3624A (**M**)	5 Hz–2000 Hz
	HI-3604 (**E, M**)	30 Hz–2000 Hz
	HI-3627 (3-axis **M,** recorder output)	5 Hz–2000 Hz
Magnetic Sciences International Acton, Massachusetts, USA	MSI-95 (1-axis **M**)	25 Hz–3000 Hz
	MSI-90 (1-axis **M**)	18 Hz–3300 Hz
	MSI-25 (1-axis **M**)	40 Hz–280 Hz
Physical Systems International Holmes Beach, Florida, USA	FieldMeter (1-axis **E**, **M**)	16 Hz–5000 Hz
	FieldAnalyzer (1-axis **E**, 3-axis **M**, waveform)	1 Hz–500 Hz
Sypris Test and Measurement Orlando, Florida, USA	4070 (1-axis **M**)	40 Hz–200 Hz
	4080 (3-axis **M**)	40 Hz–600 Hz
	4090 (3-axis **M**)	50 Hz–300 Hz
	7030 (3-axis **M**)	10 Hz–50 000 Hz
Tech International Corp. Hallandale, Florida, USA	CellSensor (1-axis **M** & **RF**)	~50 Hz–~835 MHz

Table 9 (contd)

Company, location	**Meter, field type**	**Frequency range**
Technology Alternatives Corp. Miami, Florida, USA	ELF Digital Meter (**M**)	20 Hz–400 Hz
	ELF/VLF Combination Meter (**M**)	20 Hz–2000 Hz ELF; 10.000 Hz–200 000 Hz VLF
Walker LDJ Scientific, Inc. Worcester, Massachusetts, USA	ELF 45D (1-axis **M**)	30 Hz–300 Hz
	ELF 60D (1-axis **M**)	40 Hz–400 Hz
	ELF 90D (3-axis **M**)	40 Hz–400 Hz
	BBM-3D (3-axis **M**, ELF & VLF)	12 Hz–50 000 Hz

Source: Microwave News (2002) and industry sources

E, electric; **M**, magnetic (50 or 60 Hz); **RF**, radiofrequency; **ELF**, extremely low frequency; **VLF**, very low frequency

[a] Some instruments are suitable for measuring both magnetic and electric fields.

Specialized wave-capture instruments, such as the portable MultiWave system, can measure static and time-varying magnetic fields at frequencies of up to 3 kHz (Bowman & Methner, 2000). The EMDEX WaveCorder can also measure and record the waveform of magnetic fields for display and downloading.

In addition to measuring power-frequency fields, the Positron meter was designed to detect pulsed electric and magnetic fields or high-frequency transients associated with switching operations in the utility industry (Héroux, 1991). Only after its use in two epidemiology studies was it discovered that the readings of the commercial sensors were erratic and susceptible to interference from radiofrequency fields outside the bandwidth specification of the sensor. The interference by radio signals from hand-held walkie-talkies and other communication devices was recorded (Maruvada *et al.*, 2000).

The EMDEX Transient Counter, which has recently been developed, continuously measures changes in magnetic fields at frequencies between 2000 Hz and 220 000 Hz and reports the number of times that the change in amplitude exceeds thresholds of 5 nT and 50 nT (data from the manufacturer, 2001).

A list of some currently available instruments for measuring magnetic fields is given in Table 9.

1.2.2 *Computation methods*

For many sources, measurements are the most convenient way to characterize exposure to ELF electric and magnetic fields. However, unperturbed fields from sources such as power lines can also be easily characterized by calculations. Calculated electric field intensity and direction may differ from those that are measured because of the presence of conductive objects close to the source and/or near the location of interest.

The fields from power lines can be calculated accurately if the geometry of the conductors, the voltages and currents (amplitude and phase angle) in the conductors and return paths are known. The currents flowing in the conductors of power lines are typically logged at substations and historical line-loading data may be available. However, in some cases, currents do not all return to utility facilities and may flow into the earth or into any conductor which is at earth potential, such as a neutral wire, telephone wire, shield wire or buried piping. Because the magnitude and location of the currents on these paths are not known, it is difficult or impossible to include them in computations.

The simplest calculations assume that the conductors are straight, parallel and located above, and parallel to, an infinite flat ground plane. Balanced currents are also typically assumed. Calculations of magnetic fields that do not include the contribution of small induced currents in the earth are accurate near power lines, but may not be so at distances of some hundreds of metres (Maddock, 1992). Very accurate calculations of the maximum, resultant and vector components of electric and magnetic fields are possible if the actual operating conditions at the time of interest are known, including the current flow and the height of conductors, which vary with ambient temperature and line loading.

A number of computer programs have been designed for the calculation of fields from power lines and substations. These incorporate useful features such as the calculation of fields from non-parallel conductors. While the computation of simple fields by such programs may be quite adequate for their intended purpose, it may be difficult for other investigators to verify the methods used to calculate exposures. Epidemiological studies that estimated the historical exposures of subjects to magnetic fields from power lines by calculations did not usually report using documented computer programs or publish the details of the computation algorithms, e.g. Olsen *et al.* (1993), Verkasalo *et al.* (1993, 1996), Feychting and Ahlbom (1994), Tynes and Haldorsen (1997) and UK Childhood Cancer Study Investigators (2000a). However, for exposure assessment in these studies, it is likely that the uncertainty in the historical loading on the power lines would contribute much more to the overall uncertainty in the calculated field than all of the other parameters combined (Jaffa *et al.*, 2000).

Calculations are also useful for the calibration of electric and magnetic field meters (IEEE, 1995b) and in the design of animal and in-vitro exposure systems, e.g. Bassen *et al.* (1992), Kirschvink (1992), Mullins *et al.* (1993).

1.3 Exposure assessment

1.3.1 *External dosimetry*

(*a*) *Definition and metrics*

External dosimetry deals with characterization of static and ELF electric and magnetic fields that define exposure in epidemiological and experimental studies. For static fields, the field strength (or flux density) and direction unambiguously describe exposure conditions. As with other agents, the timing and duration of exposure are important parameters, but the situation is more complex in the case of ELF fields. The difficulty arises, not from the lack of ability to specify complete and unique characteristics for any given field, but rather from the large number of parameters requiring evaluation, and, more importantly, the inability to identify the critical parameters for biological interactions.

Several exposure characteristics, also called metrics, that may be of biological significance have been identified (Morgan & Nair, 1992; Valberg, 1995). These include:

- intensity (strength) or the corresponding flux density, root mean square, average or peak value of the exposure field; or a function of the field strength such as field-squared;
- duration of exposure at a given intensity;
- time (e.g. daytime versus night-time);
- single versus repeated exposure;
- frequency spectrum of the field; single frequency, harmonic content, intermittency, transients;
- spatial field characteristics: orientation, polarization, spatial homogeneity (gradients);
- single field exposure, e.g. ELF magnetic versus combined electric and magnetic field components, and possibly their mutual orientation;
- simultaneous exposure to a static (including geomagnetic field) and ELF field, with a consideration of their mutual orientation;
- exposure to ELF fields in conjunction with other agents, e.g. chemicals.

The overall exposure of a biological system to ELF fields can be a function of the parameters described above (Valberg, 1995).

(*b*) *Laboratory exposure systems*

Laboratory exposure systems have the advantage that they can be designed to expose the subjects to fields of specific interest and the fields created are measurable and controllable. Laboratory exposure systems for studying the biological effects of electric and magnetic fields are readily classified as *in vivo* or *in vitro*. Most studies of exposure *in vivo* have been in animals; few have involved humans. In-vitro studies of exposure are conducted on isolated tissues or cultured cells of human or animal origin.

One reason for studying the effects of very strong fields is the expectation that internal dose is capable of being biologically scaled. For this reason, many laboratory experiments have been performed at field strengths much higher than those normally measured in residential and occupational settings. This approach is usually used on the assumption that the amplitude of biological effects increases with field strength up to the maxima set in exposure guidelines, and the physical limitations of the exposure system.

(i) *In-vivo exposure systems*

Many in-vivo studies have used magnetostatic fields (Tenforde, 1992; see also section 4). Both iron-core electromagnets and permanent magnets are routinely used in such studies. Although it is theoretically possible to obtain even larger DC magnetic fields from iron-core devices (up to approximately 2 T), there is a limitation on the size of the active volume between the pole faces where the field is sufficiently uniform. Experimental studies of fields greater than 1.5 T are difficult because limited space is available for exposing biological systems to reasonably uniform magnetic fields.

The most commonly used apparatus for studying exposure to electric fields consists of parallel plates between which an alternating voltage (50 or 60 Hz, or other frequencies) is applied. Typically, the bottom plate is grounded. When appropriate dimensions of the plates are selected (i.e. a large area in comparison to the distance between the plates), a uniform field of reasonably large volume can be produced between the plates. The distribution of the electric-field strength within this volume can be calculated. The field becomes less uniform close to the plate edges.

A uniform field in an animal-exposure system can be significantly perturbed by two factors. An unavoidable but controllable perturbation is due to the presence of test animals and their cages. Much information is available on correct spacing of animals to ensure similar exposure for all test animals and to limit the mutual shielding of the animals (Kaune, 1981a; Creim *et al.*, 1984). Animal cages, drinking bottles, food and bedding cause additional perturbations of the electric field (Kaune, 1981a). One of the most important causes of artefactual results in some studies is induction of currents in the nozzle of the drinking-water container. If the induced currents are sufficiently large, animals experience electric microshocks while drinking. Corrective measures have been developed to alleviate this problem (Free *et al.*, 1981). Perturbation of the exposure field by nearby metallic objects is easy to prevent. The faulty design, construction and use of the electric-field-exposure facility can result in unreliable exposure over and above the limitations that normally apply to animal bioassays.

A magnetic field in an animal-exposure experiment is produced by current flowing through an arrangement of coils. The apparatus can vary from a simple set of two Helmholtz coils (preferably square or rectangular to fit with the geometry of cages), to an arrangement of four coils (Merritt *et al.*, 1983), to more complicated coil systems (Stuchly *et al.*, 1991; Kirschvink, 1992; Wilson *et al.*, 1994; Caputa & Stuchly, 1996). The main objectives in designing apparatus for exposure to magnetic fields are (1) to ensure the maximal uniformity of the field within as much as possible of the volume encompassed by the coils, and (2) to minimize the stray fields outside the coils, so that sham-exposure apparatus can be placed in the same room. Square coils with four windings arranged according to the formulae of Merritt *et al.* (1983) best satisfy the field-uniformity requirement. Limiting the stray fields is a challenge, as shielding magnetic fields is much more complex than shielding electric fields. Non-magnetic metal shields only slightly reduce the field strength. Only properly designed multilayer-shielding enclosures made of high-permeability materials are effective. An alternative solution relies on partial field cancellation. Two systems of coils placed side by side or one above the other form a quadrupole system that effectively decreases the magnetic field outside the exposure system (Wilson *et al.*, 1994). An even greater reduction is obtained with a doubly compensating arrangement of coils. Four coils (each consisting of four windings) are arranged side by side and up and down; coils placed diagonally are in the same direction as the field, and the neighbouring coils are in the opposite direction (Caputa & Stuchly, 1996).

Likely artefacts associated with magnetic-field-exposure systems include heating, vibrations and audible or high-frequency (non-audible to humans) noise. These factors can be minimized (although not entirely eliminated) with careful design and construction, which can be costly. The most economical and reliable way of overcoming these problems is through essentially identical design and construction of the field- and sham-exposure systems except for the current direction in bifilarly wound coils (Kirschvink, 1992; Caputa & Stuchly, 1996). This solution provides for the same heating of both the control and exposed systems. Vibration and noise are usually not exactly the same but are similar. To limit the vibration and noise, the coil windings should be restricted mechanically in their motion.

Another important feature of a properly designed magnetic-field system is shielding against the electric field produced by the coils. Depending on the coil shape, the number of turns in the coil and the diameter of the wire, a large voltage drop can occur between the ends of the coils. Shielding of the coils can eliminate interference from the electric field.

(ii) *In-vitro exposure systems*

Cell and tissue cultures can be exposed to the electric field produced between parallel plates in the same way that animals are exposed. In practice, this procedure is hardly ever used, because the electric fields in the in-vitro preparation produced this way are very weak, even for strong applied fields. For instance, an externally applied field of 10 kV/m at 60 Hz results in only a fraction of a volt per metre in the culture (Tobey *et al.*, 1981; Lymangrover *et al.*, 1983). Furthermore, the field strength is usually not uniform throughout the culture, unless the culture is thin and is placed perpendicular or parallel to the field. A practical solution involves the placement of appropriate electrodes in the cultures. Agar or other media bridges can be used to eliminate the problem of electrode contamination (McLeod *et al.*, 1987). A comprehensive review of in-vitro exposure systems has recently been published (Misakian *et al.*, 1993).

The shape and size of the electrodes determine the uniformity of the electric field and associated spatial variations of the current density. Either accurate modelling or measurements, or preferably both, should be performed to confirm that the desired exposure conditions are achieved. Additional potential problems associated with this type of exposure system are the heating of the medium and accompanying induced magnetic fields. Both of these factors can be evaluated (Misakian *et al.*, 1993).

Coils similar to those used for animal studies can be used for in-vitro experiments (Misakian *et al.*, 1993). The greatest uniformity is achieved along the axis within the volume enclosed in the solenoid. One great advantage of solenoids over Helmholtz coils is that the uniform region within the solenoid extends from the axis across the whole of the cross-sectional diameter.

In in-vitro studies, special attention should be paid to ambient levels of 50 or 60 Hz and to other magnetic fields. Magnetic flux densities from incubators unmodified for bioeffect studies may have background gradients of magnetic fields ranging from a few tenths of a microtesla to approximately 100 μT. Similarly, some other laboratory equipment with an electric motor might expose biological cells to high, but unaccounted for, magnetic flux densities. Specially designed in-vitro systems can avoid these problems. Exposure to magnetic fields that is unaccounted for or is at an incorrect level, as well as the critical influence of temperature and carbon dioxide concentration on some cell preparations, can lead to unreliable findings in laboratory experiments (Misakian *et al.*, 1993).

In some in-vitro studies, simultaneous exposure to alternating and static magnetic fields is used in a procedure intended to test the hypothesis of possible 'resonant' effects. Almost all the requirements for controlled exposure to the alternating field apply to the static field. Some precautions are not required in static field systems. For example, static systems have no vibrations (with the possible exception of on and off switching) so prevention of vibrations is unnecessary. In experiments involving static magnetic fields, the earth's magnetic field should be measured and controlled locally.

1.3.2 *Internal dosimetry modelling*

(*a*) *Definition for internal dosimetry*

At ELF, electric fields and magnetic fields can be considered to be uncoupled (Olsen, 1994). Therefore, internal dosimetry is also evaluated separately. For simultaneous exposure to both fields, internal measures can be obtained by superposition. Exposure to either electric or magnetic fields results in the induction of electric fields and associated current densities in tissue. The magnitudes and spatial patterns of these fields depend on the type of field (electric or magnetic), its characteristics (frequency, magnitude, orientation), and the size, shape and electrical properties of the exposed body (human, animal). Exposure to electric fields also results in an electric charge on the body surface.

The primary dosimetric measure is the induced electric field in tissue. The most frequently reported dosimetric measures are the average, root-mean-square and maximum induced electric field and current density values (Stuchly & Dawson, 2000). Additional measures include the 50th, 95th and 99th percentiles which indicate values not exceeded in a given volume of tissue, e.g. the 99th percentile indicates the dosimetric measure exceeded in 1% of a given tissue volume (Kavet *et al.*, 2001). The electric field in tissue is typically expressed in μV/m or mV/m and the current density in μA/m^2 or mA/m^2. Some safety guidelines (International Commission on Non-Ionizing Radiation Protection (ICNIRP), 1998) specify exposure limits measured as the current density averaged over 1 cm^2 of tissue perpendicular to the direction of the current.

The internal (induced) electric field **E** and conduction current density **J** are related through Ohm's law:

$$\mathbf{J} = \sigma\mathbf{E}$$

where the bold symbols denote vectors and σ is the bulk tissue conductivity which may depend on the orientation of the field in anisotropic tissues (e.g. muscle).

(*b*) *Electric-field dosimetry*

Early dosimetry models represented the human (or animal) body in a simplified way, as reviewed elsewhere (Stuchly & Dawson, 2000). During the past 10 years, several laboratories have developed sophisticated heterogeneous models of the human body (Gandhi & Chen, 1992; Zubal *et al*., 1994; Gandhi, 1995; Dawson *et al*., 1997; Dimbylow, 1997). These models partition the body into volumes of different conductivity. Typically, over 30 distinct organs and tissues are identified and represented by cubic cells (voxels) with 1–10-mm sides. Voxels are assigned a conductivity value based on the measured values reported by Gabriel *et al*. (1996). A model of the human body constructed from several geometrical bodies of revolution has also been used (Baraton *et al*., 1993; Hutzler *et al*., 1994).

Various methods have been used to compute induced electric fields in these high-resolution models. Because of the low frequency involved, exposures to electric and magnetic fields are considered separately and the induced vector fields are added, if needed. Exposure to electric fields is generally more difficult to compute than exposure to magnetic fields, since the human body significantly perturbs the electric field. Suitable numerical methods are limited by the highly heterogeneous electrical properties of the human body and the complex external and organ shapes. The methods that have been successfully used so far for high-resolution dosimetry are: the finite difference method in frequency domain and time domain, and the finite element method. The advantages and limitations of each method have been reviewed by Stuchly and Dawson (2000). Some of the methods and computer codes have been extensively verified by comparison with analytical solutions (Dawson & Stuchly, 1997).

Several numerical evaluations of the electric field and the current density induced in various organs and tissues have been performed (Dawson *et al*., 1998; Furse & Gandhi, 1998; Dimbylow, 2000; Hirata *et al*., 2001). Average organ (tissue) and maximum voxel values of the electric field and current density are typically reported. In the recent studies (Dimbylow, 2000; Hirata *et al*., 2001), the maximum current density was averaged over 1 cm^2 for excitable tissues. The latter computation is clearly aimed at testing compliance with the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guideline (1998) and the commentary published thereafter (Matthes, 1998).

The induced electric fields computed in various laboratories are in reasonable agreement (Stuchly & Gandhi, 2000). As expected, smaller differences are observed between calculated electric fields than between calculated values for current density.

The observed differences can be explained by differences between the body models and the conductivity values allocated to different tissues.

The differences observed in the results of high-resolution models depend in part upon the conductivity values assumed (Dawson *et al.*, 1998). In general, the lower the induced electric fields (the higher the current density) the higher the conductivity of tissue. The exceptions are those parts of the body associated with concave curvature, e.g. the tissue surrounding the armpits, where the electric field is enhanced. For the whole body, the computed average values do not differ by more than 2% (Stuchly & Dawson, 2000).

The resolution of the model influences the accuracy with which the induced fields are evaluated in various organs. Organs that are small in any dimension are poorly represented by large voxels. The maximum induced electric field is higher for the finer resolution. The differences are typically of the order of 50–190% for voxels of 3.6-mm sides compared to 7.2-mm voxels (Stuchly & Dawson, 2000).

The highest induced fields are found in a body that is in contact with perfect ground through both feet. The average values for the organs or tissues of a ‘grounded’ body are about two or three times those for a body in free space (Dawson *et al.*, 1998), and intermediate values are obtained for various degrees of separation from the ground. This dependence on the contact with or separation from a perfect ground is in agreement with earlier experimental data (Deno & Zaffanella, 1982).

The main features of dosimetry for exposure of a person standing in an ELF electric field can be summarized as follows:

- The magnitudes of the electric fields in tissue are typically 10^{-5}–10^{-8} lower than the magnitude of the external field.
- For exposure to external fields from power lines, the predominant direction of the induced fields is also vertical.
- The largest fields in a human body are induced by a vertical electric field when the feet are in contact with a perfectly conducting ground plane.
- The weakest fields are induced in a body when it is in free space, i.e. infinitely far from the ground plane.
- The short-circuit current for a body in contact with perfect ground is determined by the size and shape of the body (including posture), rather than its tissue conductivity.

Table 10 summarizes the computed internal electric fields for a model of an adult body in a vertical field of 1 kV/m at 60 Hz (Kavet *et al.*, 2001), where the body (1.77 m in height and 76 kg in weight) makes contact with a perfectly conducting ground with both feet. Table 11 summarizes computed internal electric fields for a model of a five-year-old child (1.10 m in height and 18.7 kg in weight) (Hirata *et al.*, 2001). Selected conductivity values are given in Table 2 of the General Introduction. Dawson *et al.* (2001) demonstrated that the voxel maximum values are significantly overestimated, and the 99th percentiles are therefore more representative.

Table 10. Calculated electric fields (mV/m) in a vertical uniform electric field (60 Hz, 1 kV/m) induced in a model of a grounded adult human body[a]

Tissue/organ	E_{avg}	$E_{99\ percentile}$	E_{max}
Blood	1.4	8.9	24
Bone marrow	3.6	34	41
Brain	0.86	2.0	3.7
Cerebrospinal fluid	0.35	1.0	1.6
Heart	1.4	2.8	3.6
Kidneys	1.4	3.1	4.5
Lungs	1.4	2.4	3.6
Muscle	1.6	10	32
Prostate	1.7	2.8	3.1
Spleen	1.8	2.6	3.2
Testes	0.48	1.2	1.6

Modified from Kavet *et al*. (2001)

[a] Corresponding current densities can be computed from tissue conductivity values (see Table 2, General Introduction)

Table 11. Calculated electric fields (mV/m) in a vertical uniform electric field (60 Hz, 1 kV/m), induced in a model of the grounded body of a child

Tissue/organ	E_{avg}	$E_{99\ percentile}$	E_{max}
Blood	1.5	9.2	18
Bone marrow	3.7	35	42
Brain	0.7	1.6	3.1
Cerebrospinal fluid	0.28	0.87	1.4
Heart	1.6	3.1	3.7
Lungs	1.6	2.6	3.7
Muscle	1.7	10	31

Modified from Hirata *et al*. (2001)

Exposure in occupational situations, e.g. in a substation, where a person is close to a conductor at high potential, induces greater electric fields in certain organs (e.g. brain) than would be predicted from the measured exposure field 1.5 m above ground (Potter *et al*., 2000). This is to be expected, since the external field increases above the ground.

(*c*) *Magnetic-field dosimetry*

Early dosimetry models represented the body as a circular loop corresponding to a given body contour to determine the induced electric field or current density based on Faraday’s law:

$$|\mathbf{J}| = \pi f \sigma \mathrm{r}\, |\mathbf{B}|$$

where f is the frequency, r is the loop radius and **B** is the magnetic flux density vector perpendicular to the current loop. Similarly, ellipsoidal loops have been used to fit the body shape better.

More realistic models of the human body have been analysed by the numerical impedance method (Gandhi & De Ford, 1988; Gandhi & Chen, 1992; Gandhi *et al.*, 2001) and the scalar potential finite difference technique (Dawson & Stuchly, 1998; Dimbylow, 1998). The dosimetry data available for magnetic fields are more extensive than those for electric fields. The effects of tissue properties in general (and specifically muscle anisotropy), field orientation with respect to the body and, to a certain extent, body anatomy have been investigated (Dawson *et al.*, 1997; Dawson & Stuchly, 1998; Dimbylow, 1998). In the past, the largest loop of current fitted within a body part, e.g. head or heart, was often used to calculate the maximum current density in that body part. This is now known to underestimate the maximum induced field and the current densities (Stuchly & Dawson, 2000)

The main features of dosimetry for exposure to uniform ELF magnetic fields can be summarized as follows:

- The induced electric fields depend on the orientation of the magnetic field with respect to the body.
- For most organs and tissues, the magnetic field orientation perpendicular to the torso (front-to-back) gives maximum induced quantities.
- For the brain, cerebrospinal fluid, blood, heart, bladder, eyes and spinal cord, the strongest induced electric fields are produced by a magnetic field directed towards the side of the body.
- Magnetic fields oriented along the vertical body axis induce the weakest electric fields.
- Stronger electric fields are induced in bodies of larger size.

Table 12 lists the electric fields induced in certain organs and tissues by a 60-Hz, 1-μT magnetic field oriented front-to-back (Dawson *et al.*, 1997; Dawson & Stuchly, 1998; Kavet *et al.*, 2001).

The exposure of humans to relatively high magnetic flux densities occurs most often in occupational settings. Numerical modelling has been applied mostly to workers exposed to high-voltage power lines (Baraton & Hutzler, 1995, Stuchly & Zhao, 1996; Dawson *et al.*, 1999a,b,c). In these cases, current-carrying conductors can be represented as infinite straight-line sources. However, some of the exposure occurs in more complex scenarios, two of which have been analysed, and a more realistic representation of the source conductors based on finite line segments has been used

(Stuchly & Dawson, 2000). Table 13 lists calculated electric fields for the two representative exposure scenarios illustrated in Figure 6 (Stuchly & Dawson, 2000).

Table 12. Calculated electric fields (μV/m) in a uniform magnetic field (60 Hz, 1 μT) oriented front-to-back induced in a model of an adult human

Tissue/organ	E_{avg}	$E_{99\ percentile}$	E_{max}
Blood	6.9	23	83
Bone marrow	16	93	154
Brain	11	31	74
Cerebrospinal fluid	5.2	17	25
Heart	14	38	49
Kidneys	25	53	71
Lungs	21	49	86
Muscle	15	51	147
Prostate	17	36	52
Spleen	41	72	92
Testes	15	41	73

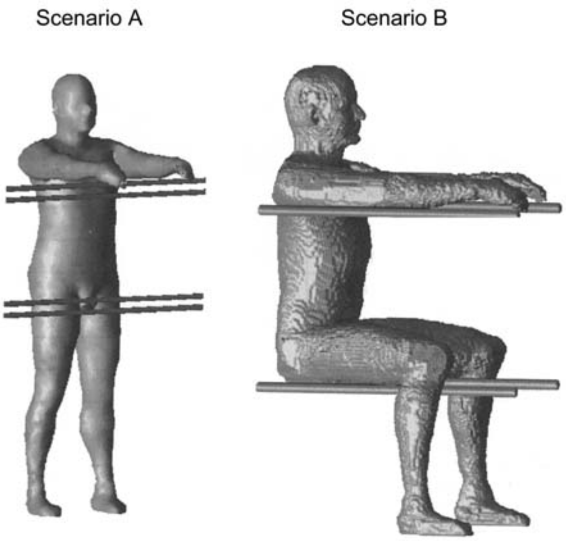
Modified from Kavet *et al*. (2001)

Table 13. Calculated electric fields (mV/m) induced in a model of an adult human for the occupational exposure scenarios shown in Figure 6 (total current in conductors, 1000 A)

Tissue/organ	Scenario A		Scenario B	
	E_{max}	E_{rms}	E_{max}	E_{rms}
Blood	20	3.7	15	2.4
Bone	90	11	58	7.2
Brain	22	4.6	28	5.9
Cerebrospinal fluid	9.2	2.3	14	3.7
Heart	27	11	9.0	3.2
Kidneys	22	7.9	2.8	0.9
Lungs	31	10	9.9	2.9
Muscle	59	6.9	33	5.5
Prostate	5.5	1.9	2.6	1.2
Testes	18	5.5	2.7	1.2

Modified from Stuchly & Dawson (2000)

Figure 6. Body positions in two occupational exposure scenarios



From Stuchly & Dawson (2000)
The current in each conductor is 250 A for a total of 1000 A in four conductors.

(*d*) *Contact-current dosimetry*

Contact currents produce electric fields in tissue similar to those induced by external electric and magnetic fields. Contact currents are encountered in a dwelling or workplace when a person touches conductive surfaces at different potentials and completes a path for current flow through the body. The current pathway is usually from hand-to-hand and/or from a hand to one or both feet. Sources of contact current may include an appliance chassis or household fixture that, because of typical residential wiring practices, carries a small potential above a ground. Other sources of contact current are conductive objects situated in an electric field, such as a vehicle parked under a power line. The importance of contact currents has been suggested by Kavet *et al*. (2000). Recently, electric fields have been computed in a model of a child with electrodes on hands and feet simulating contact current (Dawson *et al.*, 2001). The most common source of exposure to contact current is touching an ungrounded object while both feet are grounded. The electric fields calculated to be induced in the bone marrow of the hand and arm of a child for a 1-μA contact current are shown in Table 14. Electric fields above 1 mV/m can be produced in the bone marrow of a child from a low contact current of 1 μA. In residential settings such a current could result from an open-circuit voltage of only 100 mV, which is not uncommon. A total resistance of 5–10 kΩ is representative (Kavet *et al.*, 2000). Provided that there is good contact to the ground, only 5–10 mV is needed to produce a current of 1–2 μA. Contact current with vehicles in an electric field

Table 14. Calculated electric field (mV/m) induced by a contact current of 60 Hz, 1 μA, in voxels of bone marrow of a child

Body part	E_{avg}	$E_{99\ percentile}$
Lower arm	5.1	14.9
Upper arm	0.9	1.4
Whole body	0.4	3.3

Modified from Dawson *et al.* (2001)

(e.g. under high-voltage power lines) typically ranges from 0.1 mA per 1 kV/m for a car to 0.6 mA per 1 kV/m for a large truck (Deno & Zaffanella, 1982).

(*e*) *Biophysical relevance of induced fields*

The lowest electric field in tissue to be associated with well-documented biological effects (not necessarily harmful) has been estimated as 1 mV/m (Portier & Wolfe, 1998). It is interesting to compare the different exposure conditions that produce an internal field of this magnitude. Table 15 shows the average exposure to electric and magnetic fields required to induce a field of 1 mV/m in selected tissues (Stuchly & Dawson, 2000). Although the mechanisms for biological effects of fields at 1 mV/m are unclear, it is, nevertheless, interesting to compare the electric fields induced in humans by exposure to residential magnetic fields, electric fields and contact currents. Table 16 shows that the electric field induced in a model of a child's bone marrow (i.e. the tissue involved in leukaemia) is 10 times greater for the exposure to a contact current than for exposure to either the maximum electric or magnetic field encountered in a dwelling (Kavet *et al.*, 2000).

(*f*) *Microscopic dosimetry*

Macroscopic dosimetry that describes induced electric fields in various organs and tissues can be extended to more spatially refined models of subcellular structures to predict and understand biophysical interactions. The simplest cellular model for considering linear systems requires evaluation of induced fields in various parts of a cell. Such models, for instance, have been developed to understand neural stimulation (Plonsey & Barr, 1988; Basser & Roth, 1991; Reilly, 1992; Malmivuo & Plonsey, 1995). Computations are available as a function of the applied electric field and its frequency. Because cell membranes have high resistivity and capacitance (nearly constant for all mammalian cells and equal to 0.5–1 μF/cm^2) (Reilly, 1992), at sufficiently low frequencies, high fields are produced at the two poles of the membrane. The field is nearly zero inside the cell, as long as the frequency of the applied field is below the membrane relaxation frequency (~ 1 MHz) (Foster & Schwan, 1995). The total

Table 15. Calculated electric (grounded model) or magnetic field (front to back) source levels needed to induce average (E_{avg}) and maximum (E_{max}) electric fields of 1 mV/m

Organ	Electric field exposure		Magnetic field exposure	
	E_{avg} = 1 mV/m	E_{max} = 1 mV/m	E_{avg} = 1 mV/m	E_{max} = 1 mV/m
Blood	0.72 kV/m	61 V/m	115 µT	15 µT
Bone	0.31 kV/m	22 V/m	46 µT	6.0 µT
Brain	1.2 kV/m	355 V/m	87 µT	26 µT
Cerebrospinal fluid	3.3 kV/m	901 V/m	233 µT	52 µT
Heart	0.93 kV/m	457 V/m	56 µT	20 µT
Kidneys	0.97 kV/m	412 V/m	43 µT	18 µT
Liver	0.79 kV/m	372 V/m	38 µT	11 µT
Lungs	0.99 kV/m	435 V/m	46 µT	14 µT
Muscle	0.76 kV/m	43 V/m	57 µT	6.9 µT
Prostate	0.68 kV/m	442 V/m	58 µT	28 µT
Testes	1.8 kV/m	769 V/m	53 µT	20 µT
Whole body	0.59 kV/m	21 V/m	49 µT	1.3 µT

Modified from Stuchly & Dawson (2000)

Table 16. Calculated average electric field (mV/m) induced by an electric field, magnetic field and contact current in child's bone marrow (model)

Exposure	Scenario	Intensity	Electric field (mV/m)
Magnetic field	Uniform, horizontal and frontal exposure	10 µT	0.2
Electric field	Uniform, vertical grounded	100 V/m	0.3
Contact current	Current injection into shoulders	18 µA	3.5

Modified from Kavet *et al.* (2000)

membrane resistance and capacitance define this frequency; thus, it depends on the cell size (total membrane surface). The larger the cell, the higher the induced membrane potential for the same applied field, but the larger the cell, the lower the membrane relaxation frequency.

Gap junctions connect many cells. A gap junction is an aqueous pore or channel through which neighbouring cell membranes are connected. Thus, cells can exchange ions, for example, providing local intercellular communication (Holder *et al.*, 1993). In gap-junction-connected cells there is electrical coupling between the cytoplasm of adjoining cells and such systems have previously been modelled as leaky cables (Cooper, 1984). Simplified models have also been used, in which a group of gap-junction-connected cells is represented by a large cell of the same size (Polk, 1992).

Using such models, relatively large membrane potentials have been estimated, even for applied fields of only moderate intensity. A numerical analysis has been performed to compute membrane potentials in more realistic multiple-cell models (Fear & Stuchly, 1998). Simulations have indicated that simplified models such as a single cell or leaky-cable can be used only in some specific situations. Even when these models are appropriate, equivalent cells must be constructed, in which the cytoplasm properties are modified to account for the properties of gap-junctions. These models are reasonably accurate for very small assemblies of cells of certain shapes exposed at very low frequencies. As the size of the cell-assembly increases, the membrane potential, even at static fields, does not increase linearly with dimensions as it does for very short elongated assemblies. There is also a limit to the membrane potential for assemblies of other shapes.

From this linear model of gap-connected cells, it can be concluded that, at 50 or 60 Hz, an induced membrane potential of 0.1 mV is not attained in any organ or tissue of the human body exposed to a uniform magnetic flux density of up to 1 mT or to an electric field of 10 kV/m or less (Fear & Stuchly, 1998). These external field levels are much higher than those that elicit 1 mV/m in the bone marrow.

1.4 Biophysical mechanisms

Beyond the well-established mechanisms of interaction described above, such as the induction of currents from time-varying magnetic fields, a number of hypotheses have been advanced to explain ELF and static field interactions. These include radical-pair mechanisms; charge-to-mass signature; biogenic magnetite; etc.

1.4.1 *Induced currents*

The role of induced currents has been discussed by Adair (1991) who argued that because currents induced by ambient-level magnetic fields are comparable to, or smaller than, those resulting from thermal fluctuations, they must have little physiological significance. This argument is based on calculations of the thermal (or 'kT') noise developed in the cell membrane. The four major sources of electrical noise in biological membranes are:

— Johnson–Nyquist thermally-generated electrical noise;
— 1/f noise produced by ion current through membrane channels;
— 'shot' noise resulting from the discrete nature of ionic charges; and
— endogenous fields produced by electrically active organs such as the heart, muscles and the nervous system (Tenforde, 1995).

However, it must be remembered that the electrical characteristics of the membrane are different from those of the other regions of the cell. Taking this into consideration, conclusions have been reached concerning the potential effects of weak ELF magnetic fields. For example, Adair (1991) calculated that the theoretical threshold sensitivity for biological effectiveness due to Faraday induction by ELF magnetic fields was much larger. This threshold is much higher than those reported from a variety of laboratory experiments (Fitzsimmons *et al.*, 1995; Jenrow *et al.*, 1996; Harland & Liburdy, 1997; Zhadin *et al.*, 1999; Blackman *et al.*, 2001). If some of these experimental results are correct, the discrepancy between theoretical and experimental results indicates that the thermal-noise arguments have to be reconsidered. Indeed, low thresholds of 4 mV/m and 10 mV/m were calculated by Polk (1993) and Tenforde (1993), respectively, based on a redistribution of charges in the counterion layer rather than on changes in transmembrane potential. Amplification due to the electric coupling of large arrays of cells must also be taken into account in the estimation of threshold values.

1.4.2 *Radical-pair mechanism*

Increasing attention is being paid to the possibility that static and ELF magnetic fields may affect enzymatic processes that involve radical pairs (radical-pair mechanism). The radical-pair mechanism is a well established physical mechanism for describing how applied magnetic flux densities as low as 0.1–1 mT can affect chemical or biochemical reactions nonthermally (Walleczek, 1995). The simplified radical-pair mechanism can be summarized as follows: according to Pauli's exclusion principle, two valence electrons of the same orbital differ in their quantum spin number and a pair can be represented with one electron having the spin up (↑) and the other a spin down (↓). When a molecular bond is broken, a pair of free radicals is produced in the so-called singlet state (↑↓) which can either recombine to the original molecule or separate into two free radicals. However, if the relative orientation of the spins is altered (interconversion from singlet to triplet), the kinetics of recombination are modified. Three types of process can change the orientation of the spins:

— hyperfine coupling (linked to the magnetic environment of the pair);
— differences in Larmor precession rates ('Δg' mechanism); and
— crossing from one energy level to another.

The first process, which corresponds to a decrease of the rate of the interconversion with increasing field strength, is the most likely to occur at low field-strength. Since the lifetime of the radical pair (nano- to microseconds) is much shorter than the period of the ELF signal (~ 20 ms), the ELF magnetic field can be considered as static when considering processes consisting of a single elementary chemical reaction. However, in biochemical systems involving enzymes, in which sequences of elementary reactions can lead to oscillations of concentrations of intermediate species occurring at ELFs, the external field could, in principle, couple to the system and have an effect even at low field-strength (Walleczek, 1995; Eichwald & Walleczek, 1997), possibly in the μT range, though arguments have been advanced that this could not occur at 5 μT (Adair, 1999). Experimental evidence for the radical-pair mechanism in biological processes at field strengths below 500 μT is still lacking (Brocklehurst & McLauchlan, 1996).

1.4.3 *Effects related to the charge-to-mass ratio of ions*

The results of several experimental studies suggest that consideration of some ELF magnetic field interactions requires that the static magnetic field be taken into account as well. The ion cyclotron resonance (ICR) model (Liboff, 1985) proposes that ion transfer through cell membranes is affected by cyclotron resonance when an alternating electric or magnetic field is superimposed on a static magnetic field, e.g. the geomagnetic field. It is based on the fact that the cyclotron resonance frequency of several physiologically important ions like Na^+, K^+, Mg^{2+} and Ca^{2+} falls into the ELF range. For example, for Mg^{2+} the resonance frequency would be 61.5 kHz in a static magnetic field of 50 μT, as can be calculated from the formula below (Liboff, 1985; Polk, 1995):

$$\omega_c = 2\,\pi f_c = \frac{q\,B_{DC}}{m}$$

where ω_c is the angular frequency of the alternating magnetic field, B_{DC} is the intensity of the static field, and q/m is the ionic charge-to-mass ratio. Despite the many reports (Thomas *et al.*, 1986; Rozek *et al.*, 1987; Smith *et al.*, 1987; Ross, 1990; Lerchl *et al.*, 1991; Liboff *et al.*, 1993; Smith *et al.*, 1993; Deibert *et al.*, 1994; Jenrow *et al.*, 1995; Zhadin *et al.*, 1999) that have indicated that such combinations of fields are effective in altering biological responses, there is no definitive experimental evidence and other authors have failed to replicate these effects (e.g. Parkinson & Hanks, 1989; Liboff & Parkinson, 1991; Parkinson & Sulik, 1992; Coulton & Barker, 1993).

Most importantly, there is no accepted explanation at either the microscopic or molecular level of how such field combinations could be effective. Therefore, this unique signature must, at present, be regarded as tentative and purely empirical in nature. There is some experimental evidence (Smith *et al.*, 1987) to indicate that higher frequency harmonics are also effective, following the allowed harmonic relation $f_n = (2n + 1)\, f_o$, n = 0, 1, 2, 3, …. The same authors also observed that, if all other parameters remain the same, small changes in B_{DC} (intensity of the static field) could shift the charge-to-mass ratio given above from one ionic species to another, with a totally different resultant change in the expected biological response. The implication is that, for one specific value of B_{AC} (intensity of the alternating field), there may be markedly contrasting biological outcomes if exposure to ELF fields occurs in different static fields. The geomagnetic field varies substantially over the earth’s surface, and from place to place within the same building due to local perturbations. If interaction hypotheses based upon the ion charge-to-mass ratios were valid and furthermore were a cause of cancer, then it might be difficult for epidemiological studies to capture associations with exposure to ELF magnetic fields (Smith *et al.*, 1987).

From a theoretical model, Lednev (1991) suggested that the cyclotron resonance frequency appears in the transition probability of an excited state of a charged oscillator (e.g. Ca^{2+}) located in one of the binding sites of a protein. This parametric resonance mechanism makes use of Zeeman splitting of the energy levels in a magnetic field. In addition to the ionic charge-to-mass ratio and the static field intensity, which are both well-defined experimental parameters, the transition probability p(B) is also dependent on B_{AC}, a feature that was not considered in the original hypothesis (Liboff, 1985).

The field-dependent part of the parametric resonance mechanism transition probability is to a first approximation:

$$p(B) = (-1)^n K J_n (nB_{AC}/B_{DC})$$

where K is a constant and J_n is the nth order Bessel function with argument (nB_{AC}/B_{DC}).

An alternative theoretical formulation, called the ion parametric resonance model (Blanchard & Blackman, 1994) is very similar to the parametric resonance mechanism model, except that it is not related to calcium-binding, but rather to enzyme activation. In the ion parametric resonance model, the transition probability becomes:

$$p(B) = (-1)^n K J_n (2nB_{AC}/B_{DC})$$

Exposure ‘windows’ are predicted in both models; the intensities at which these windows occur are entirely dependent on the respective arguments of the two Bessel functions. See section 4.3 for a description of experimental data in support of this formulation. By contrast, Adair (1992, 1998) gave reasons as to why these proposed mechanisms would not be expected to produce biological effects.

Other theoretical attempts to explain the experimental results have been made by Binhi (2000), using quantum mechanics to estimate the dissociation probability of an ion from a protein, and by Zhadin (1998), who hypothesized magnetically induced changes in the thermal energy distribution.

The hypothesis discussed above may explain the frequency ‘windows’ previously reported (Bawin & Adey, 1976; Blackman *et al.*, 1985). If so, the exposure conditions related to cyclotron resonance may have to be considered in a discussion of exposure to electric and magnetic fields taking into account the role of the local geomagnetic field.

1.4.4 *Biogenic magnetite*

Following the original discovery by Blakemore (1975) that certain bacteria use iron-rich intracytoplasmic inclusions for orientational purposes, such domain-sized magnetite (Fe_3O_4) particles have been found in other biological systems, notably the human brain (Kirschvink *et al.*, 1992). Kirschvink suggested that weak ELF magnetic fields coupling to biogenic magnetite might be capable of producing coherent biological signals. However, the number of magnetite crystals is exceeded by that of neurons by a factor of about 10 (Malmivuo & Plonsey, 1995) and, moreover, no experimental evidence exists to support this hypothesis. Based on a mathematical model, Adair (1993) has estimated that a 60-Hz magnetic field weaker than 5 μT could not generate a sufficiently large signal to be detectable in a biological system by interaction with magnetite. According to Polk (1994), reported experimental results indicate effects in mammals of 50-Hz fields at the 1-μT level. Rather strong static magnetic fields are required to affect the orientation behaviour of honey bees, which depends, in part, upon the influence of the geomagnetic field on magnetite in the bee's abdomen (Kirschvink *et al.*, 1997).

1.4.5 *Other mechanisms*

Electric fields can increase the deposition of charged airborne particles on surfaces. It has been suggested that this well-known phenomenon could lead to increased exposure of the skin or respiratory tract to ambient pollutants close to high-voltage AC power lines (Henshaw *et al.*, 1996; Fews *et al.*, 1999a). It is also known that the high-voltage power-lines emit corona ions, which can affect the ambient distribution of electrical charges in the air (Fews & Henshaw, 2000). Fews *et al*. (1999b) have suggested that this could enhance the deposition of airborne particles in the lung. The relevance of these suggestions to health has not been established (Jeffers, 1996; Stather *et al.*, 1996; Jeffers, 1999; Swanson & Jeffers, 1999; Fews & Henshaw, 2000; Swanson & Jeffers, 2000).