GENERAL INTRODUCTION

1. Introduction

Previous *Monographs* have considered distinct types of electromagnetic radiation: solar and ultraviolet radiation (IARC, 1992) and X- and γ-radiation (IARC, 2000). This volume is concerned with that region of the spectrum described as static and 'extremely low frequency' (ELF). Such electromagnetic energy occurs naturally or in association with the generation and transmission of electrical power and with the use of power in some appliances. It is different from electromagnetic fields and radiation consequent upon the transmission of radio and television signals and the operation of mobile phones (Figure 1).

Static electric and magnetic fields, as well as low-frequency fields, are produced by both natural and man-made sources. The natural fields are static or very slowly varying. The electric field in the air above the earth's surface is typically 100 V/m but during strong electric storms may increase 10-fold or more. The geomagnetic field is typically 50 μT (König *et al.*, 1981). Most man-made sources are at extremely low frequencies. The generation, transmission, distribution and use of electricity at 50 or 60 Hz result in widespread exposure of humans to ELF fields of the order of 10–100 V/m and 0.1–1 μT, and occasionally to much stronger fields (National Research Council, 1997; Portier & Wolfe, 1998; National Radiological Protection Board, 2001). Electrical power is an integral part of modern civilization. Because ELF fields can interact with biological systems, interest and concern about potential hazards are understandable.

The study of the effects of electric and magnetic fields on humans has a long history. Data pertaining to human health risks were first gathered in the 1960s from studies of workers with occupational exposure to ELF fields. The first data to address potential carcinogenic risks were obtained in a series of studies of adults and children with residential exposures from electrical facilities, appliances and external and internal wiring and grounding systems.

Experimental studies have expended considerable effort in the search for mechanism(s) that would predict the biological effects of the low-intensity fields that are found in residential and occupational environments. More recent investigations have focused on obtaining data to assess potential carcinogenic risks. Of particular importance are chronic bioassays that look for microscopic evidence of lesions and

Figure 1. Electromagnetic spectrum
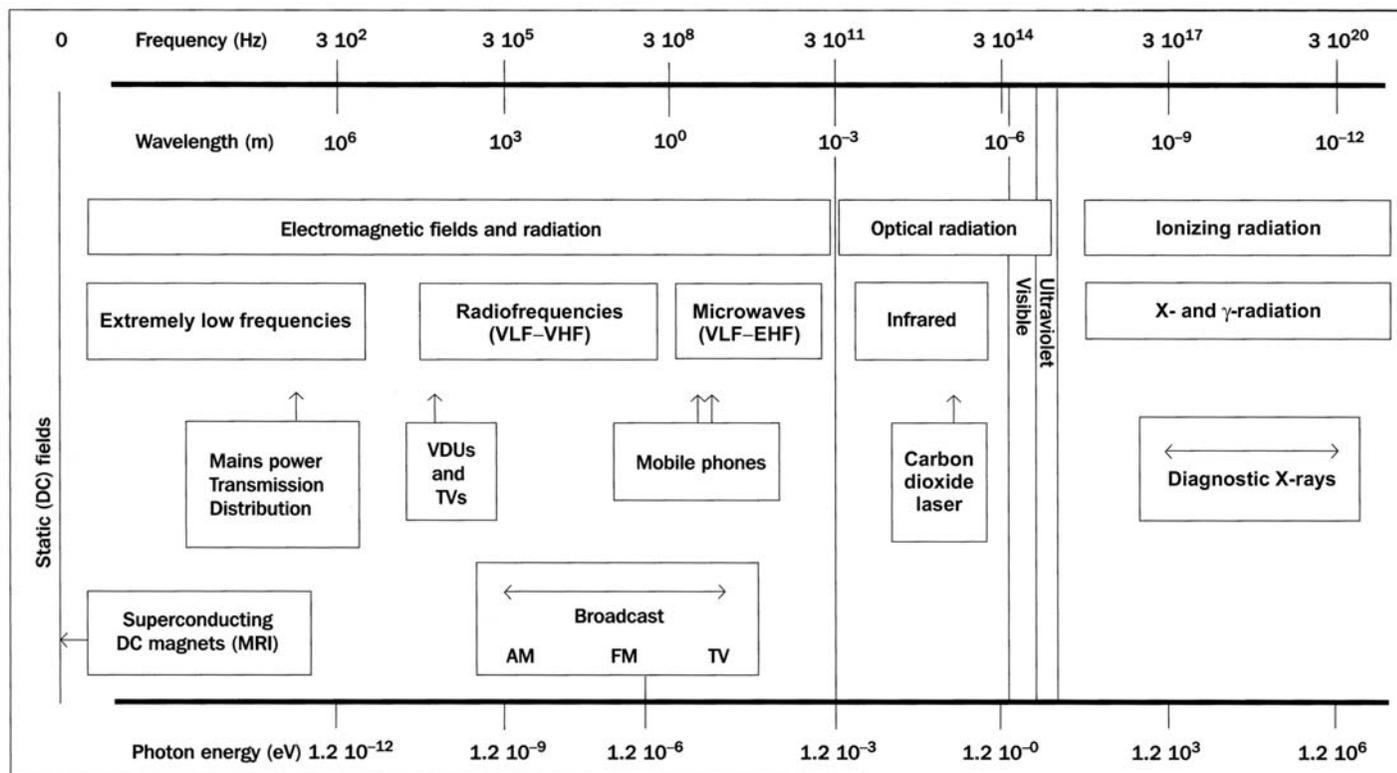
From National Radiological Protection Board (2001)
AM, amplitude modulation; DC, direct current; EHF, extremely high frequency; eV, electron volt; FM, frequency modulation; MRI, magnetic resonance imaging; TV, television; UHF, ultra high frequency; VDU, visual display unit; VHF, very high frequency; VLF, very low frequency

tumours in rodents exposed over most of their lifespan. The default assumption is that the photon energies of ELF fields, as for other forms of non-ionizing radiation, are insufficient to ionize molecules or break chemical bonds in biological systems.

The genotoxicity of electric and magnetic fields has been tested both *in vivo* and *in vitro*. The possibility that these fields may be carcinogenic has been investigated in standard tumour promotion/co-promotion systems. These involve the exposure of rodents to ELF electric and magnetic fields following, or coincident with, the initiation of skin, liver and mammary tumours by chemical initiators.

In addition to a general assessment of the data and mechanisms of toxicity, the characterization of associations between exposure to ELF magnetic fields and cancer, particularly leukaemias and brain tumours, requires focused evaluations of experimental data regarding field effects on haematopoietic cells (leukaemia), the nervous system (brain tumours) and its function and neuroendocrine and immunological factors that might be suspected of influencing susceptibility to cancer.

2. Physical characteristics of electromagnetic fields

The main focus of this *Monographs* volume is on static and time-varying fields in the ELF range of 3–3000 Hz (IEEE, 1988). Ancillary ELF phenomena, such as transients, which have frequency components in excess of 3000 Hz have also been examined for their potential contribution to the possible hazard of ELF radiation.

At frequencies above those of interest here, electromagnetic fields propagate by means of tightly coupled electric and magnetic fields (radiation). In such cases, the magnitude of the electric field can be calculated exactly if the magnetic field is known and vice versa. However, in the ELF range, electric and magnetic fields are effectively uncoupled and can be evaluated separately as if they arose from independent sources. At the low frequencies where it is customary to use the quasi-static approximation, the wavelengths of electric and magnetic fields are very large (approximately 5000 km at 60 Hz[1]) in relation to the size and distances of objects of interest (National Radiological Protection Board, 2001). Under these 'near-field' conditions (less than one wavelength), electric and magnetic fields do not effectively 'radiate' away from the source nor do they occur together in an interrelated way. The field produced by a source is better described as a zone of influence in which the forces on electrical charges oscillate in time and space. More detailed information on physical characteristics may be found elsewhere (e.g. Polk & Postow, 1995).

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[1] Wavelength (λ) is the distance in metres travelled by the wave in one period and is related to frequency (f) by $\lambda = c/f$, where c is the speed of light in a vacuum (3×10^8 m/s).

3.   Definitions, quantities and units

3.1   Electric fields

An electric field **E** exists in a region of space if a charge experiences an electrical force **F**:

$$\mathbf{F} = q\mathbf{E}$$

where q is the unit positive charge (see Table 1). The direction of the field or force corresponds to the direction that a positive charge would move in the field. Vector quantities are characterized by magnitude and direction and are displayed in bold type. Electric fields are also characterized by the electric flux density or displacement vector **D**, where $\mathbf{D} = \varepsilon\mathbf{E}$ and ε characterizes the material permittivity. The sources of electric fields are unbalanced electrical charges on conductors or other objects. For instance, on a dry winter's day, the action of pulling off a sweater can separate charges on the sweater and hair and the static electric field produced makes the wearer's hair stand on end. Electric utility facilities, including power lines, substations, appliances and building wiring are sources of time-varying electric fields. Electric fields from these sources arise from unbalanced electric charges on energized conductors. The source of the unbalanced charge is the voltage supplied by the power system.

Table 1. Quantities and units

Characteristic	Symbol[a]	SI unit	Symbol
Electric field intensity	**E**	Volt/metre	V/m
Magnetic field intensity	**B**	Tesla	T
Magnetic field	**H**	Ampere/metre	A/m
Current density	**J**	Ampere/metre squared	A/m^2
Frequency	f	Hertz	Hz
Charge density	ρ	Coulomb/metre cubed	C/m^3
Conductivity	σ	Siemens/metre	S/m
Current	I	Ampere	A
Charge	q	Coulomb	C
Force	**F**	Newton	N
Permittivity	ε	Farad per metre	F/m
Permeability	μ	Henry per metre	H/m
Permittivity of free space	ε_o	$\varepsilon_o = 8.854 \times 10^{-12}$ F/m	
Permeability of free space	μ_o	$\mu_o = 12.57 \times 10^{-7}$ H/m	

Note: 1 gauss (G) = 10^{-4} tesla (T); 1 oersted (Oe) = 1 gauss (G) in vacuum or air
[a] Vector quantities are displayed in bold type.

3.2   Current density

Electric fields exert forces on charged particles. In electrically conductive materials, including biological tissues, these forces cause an electric current to flow. The density of this current **J** across a cross-section of tissue is related to the electric field by σ, the electrical conductivity of the medium, as

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

where a homogeneous medium has been assumed.

3.3   Magnetic fields

A magnetic field **H** and associated magnetic flux density **B** exist only if electric charges are in motion, i.e. there is flow of electric current. The relationship between the two descriptions of the field is **B** = μ**H**, where for most biological materials, μ = μ_o, where μ_o is the permeability of free space (vacuum, air). The term 'magnetic field' is used in this Monograph as being equivalent to 'magnetic flux density'. Magnetic fields in turn only exert forces on a moving charge, q, as given by the Lorenz force

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$$

where the direction of the force is perpendicular to both the velocity **v** and the magnetic flux density **B**.

Static magnetic fields are formed by unidirectional, direct currents (DCs), also called steady currents, and magnetic materials (permanent magnets). Time-varying magnetic fields are produced by the same types of alternating current (AC) sources as electric fields. Time-varying magnetic fields are also sources of electric fields. Similarly, electric fields produce magnetic fields.

3.4   Magnitude

Electric and magnetic fields are vector quantities characterized by a magnitude and direction. Electric fields are most commonly described in terms of the potential difference across a unit distance. A 240-volt source connected to parallel metal plates separated by 1 m produces a field of 240 volts per metre (V/m) between the plates. Large fields are expressed in units of kilovolts per metre (kV/m, 1000 volts per metre).

The magnitude of a magnetic field is described most often by its magnetic flux density **B** in terms of magnetic lines of force per unit area. The units for magnetic flux density are webers per square metre (Wb/m^2) or Système International (SI) units of tesla (T). The equivalent old unit, often seen in the earlier literature, is gauss (G). Units of μT (100 μT = 1 G) are often used to describe ambient strengths of the magnetic field. Less commonly in the biological literature, the magnetic field strength **H** is given in amperes per metre (A/m). Occasionally, the unit of oersted (Oe) is still used.

The magnitudes of electric and magnetic fields are customarily expressed as root-mean-square (rms) values. The rms values of single-frequency sinusoidally varying fields are obtained by dividing the peak amplitude by the square root of two.

3.5   Frequency

Electric and magnetic fields are further determined by the frequency characteristics of their sources. The voltages and currents of the electric power system oscillate at 50 times per second (Hz) (60 Hz in North America) and produce a sinusoidal rise and fall in the magnitude of the associated fields at the same frequency. Electrified rail transport is sometimes powered at frequencies of 25 Hz in the USA (National Research Council, 1997) and $16\,^2/_3$ Hz in many European countries (National Radiological Protection Board, 2001). The operation of some electrical devices in the power system also produces fields at other frequencies. For example, fields can occur at multiples (harmonics) of the fundamental frequency: at 100, 150, 200 Hz, etc., for a 50-Hz system and at 120, 180, 240 Hz, etc., for a 60-Hz system.

3.6   Polarization

Fields add vectorially: both the magnitude and direction of the field must be considered in combining fields from different sources. A single conductor produces a field vector that changes its direction along a straight line. This is a linearly polarized field and has been used most often in biological studies. Multiple sources that are in phase (synchronized voltage or current waves) also produce linearly polarized fields. However, fields from multiple conductors that are not in phase, such as a three-phase distribution or transmission lines, are not necessarily linearly polarized. In these cases, the field vector is not fixed in space but rotates during a cycle, tracing out an ellipse. The field is then polarized elliptically and the ratio of the minor to major field axis defines the ellipticity or degree of polarization of the field. When the two axes of the ellipse are of equal magnitude, the ellipse forms a circle and the field is described as a circularly polarized field; when one axis is zero the field is linearly polarized.

4.   Physical interactions with biological materials

To understand the effects of electric and magnetic fields on animals and humans, their electrical properties, as well as their size and shape, have to be considered with respect to the wavelength of the external field. At ELF, the size of all mammalian and other biological bodies is a very small fraction of the wavelength.

The electrical properties of the body, namely its permittivity and permeability, relate to its interaction with the electric and magnetic fields, respectively. Human and animal bodies consist of numerous tissues, whose electrical properties differ considerably.

The permittivity $\hat{\varepsilon}$ is often written as $\hat{\varepsilon}_r \varepsilon_o$, where $\hat{\varepsilon}_r$ is the relative permittivity and ε_o is permittivity of the vacuum, $8.854 \cdot 10^{-12}$ farad/m (WHO, 1984). The permittivity determines the interactions with the electric field and the dielectric constant defines the ability to store the field energy.

Similarly, the permeability, $\hat{\mu}$, can be written as $\hat{\mu} = \hat{\mu}_r \mu_o$.

Conductive materials, i.e. those that have free electric charges (e.g. electrons and ions) are also characterized by conductivity, σ. Free charges, if in motion, can interact with both electric and magnetic fields.

Most biological tissues have a permeability equal to that of free space (air, vacuum) (Foster & Schwan, 1989, 1996). Many animal species, including humans, are known to have minuscule amounts of biogenic magnetite (Fe_3O_4) in their brains and other tissues (with permeability $\mu_r \geq 1$) (Kirschvink *et al.*, 1992).

The permittivity of biological tissues is to a large extent determined by water and electrolyte contents. Thus, tissues such as blood, muscle, liver and kidneys, which have a higher water content than tissues such as fat and lungs, have higher dielectric constants and conductivities. Both the permittivity and conductivity vary with frequency, and exhibit relaxation phenomena. The physical phenomenon responsible for the dispersion at low frequencies is counterion polarization (Foster & Schwan, 1989, 1996).

At ELF, biological bodies (e.g. humans or animals) can be considered as conductive dielectrics. Induced fields in tissues can be determined solely on the basis of their conductivity. To provide an idea of the range of conductivity values for biological tissues, Table 2 lists the most recently published conductivity measurements (Gandhi *et al.*, 2001).

Table 2. Conductivities of various tissues assumed for power-frequency electric and magnetic fields

Tissue	σ (S/m)	Tissue	σ (S/m)
Bladder	0.2	Heart	0.5
Blood	0.7	Kidney	0.09
Bone (cancellous)	0.08	Liver	0.04
Bone (compact)	0.02	Lungs	0.07
Brain (white)	0.06	Muscle	0.24
Cerebrospinal fluid	2.0	Skin	0.04
Eye sclera	0.5	Spinal cord	0.07
Fat	0.02	Testes	0.42

From Gandhi *et al.* (2001)

4.1   Static fields

A static electric field does not penetrate human and animal bodies. The field is always perpendicular to the body surface and induces surface charge density. A sufficiently large charge density may be perceived through its interaction with body hair. Indirect effects associated with induction charges on objects are well known. These range from perception, to pain, to burn resulting from a direct contact or spark discharge. There are well-established thresholds for these effects for human populations (Bernhardt, 1988).

Static magnetic fields can interact with tissues by three mechanisms (Tenforde, 1990, 1992). Firstly, electrodynamic interactions occur with ionic currents, such as blood flow or nerve impulse conduction. This interaction leads to the induction of electric field and electrical potential, e.g. across a blood vessel. This type of interaction is significant only at high flux density (≥ 1 T).

The second interaction mechanism is a magneto-mechanical effect which involves the orientation of certain biological structures in strong magnetic fields (Tenforde, 1992). Sensitivity to low intensity fields is seen in several biological species, such as certain bacteria, fish and birds. Furthermore, magnetite domains have been found in some animals, e.g. bees, tuna, salmon, turtles, pigeons, dolphins and humans. The ability to use these fields for navigation has been demonstrated for some species, e.g. bees. Studies of humans have not yielded any evidence of direction-finding based on the geomagnetic field (Tenforde, 1992).

The third mechanism relates to the Zeeman effect, whereby a magnetic field changes the energy levels of certain molecules. One consequence of the Zeeman effect is to change the probability of recombination of pairs of radicals formed in certain biochemical processes. This may result in changes in the concentration of free radicals, which can be highly reactive. This 'radical-pair mechanism' is well established in magnetochemistry (Hamilton *et al.*, 1988; McLauchlan, 1989; Cozens & Scaiano, 1993; Scaiano *et al.*, 1994; Grissom, 1995; Mohtat *et al.*, 1998), and the relevance to biological effects at low field strengths (e.g. below 500 µT) is currently under investigation (Brocklehurst & McLauchlan, 1996).

Strong static magnetic fields have several indirect effects, such as electromagnetic interference with implanted medical devices (e.g. cardiac pacemakers and defibrillators), and through forces exerted on external and implanted metallic objects. For instance, magnetic field gradients in magnetic resonance imaging facilities are known to turn metallic objects into potentially dangerous projectiles.

4.2   Extremely low-frequency (ELF) fields

The physical interactions between fields and tissues are governed by Maxwell's equations, but not all tissue components are equally interactive.

At ELFs, the photon energy is exceedingly small, thus a direct interaction causing breakage of chemical bonds and the resultant damage to DNA is not possible. At power frequencies (50 or 60 Hz), the photon energy is about 10^{-12} of the energy required to break the weakest chemical bond (Valberg $et\ al.$, 1997). It is generally agreed that whatever the interaction mechanism, it must be consistent with noise constraints. In principle, meaningful physiological changes can result only if the 'signal' produced by the field exceeds the 'noise' level present in the relevant biological system. For example, in the case of induced currents, the noise level is set by thermal processes (determined in part by kT, where k is Boltzmann's constant and T is the absolute temperature). However, a number of hypotheses listed below have sought to overcome this limitation (e.g. processes involving extremely narrow bandwidths).

The basic interaction mechanism of exposure to magnetic fields is the induction of current density in tissue: currents will always be induced in conductors exposed to time-varying magnetic fields, and current density increases with frequency and body size.

The spatial patterns of the currents induced by electric and magnetic fields are quite different from each other. In an upright human body exposed to a vertical electric field, the induced field and current flow are also vertical. Conversely, in the case of a magnetic field, the current flow forms closed loops, perpendicular to the direction of the magnetic field. General patterns of the current flow induced by exposure to magnetic fields are illustrated in Figure 2.

Figure 2. Induction of eddy currents in the human body perpendicular to (a) a vertical magnetic field and (b) a horizontal magnetic field

(a)   (b)
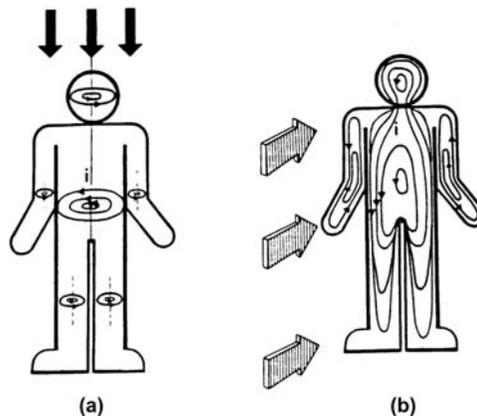
From Silny (1986)
In principle, the current density approaches zero at the centre of the loops.

Biological bodies perturb external electric fields. Because the tissue conductivity is low at low frequencies (see Table 2), the induced fields are approximately 10^5–10^8 times lower than the external fields. The perturbation of the external electric field, like the static electric field, induces surface charge on the body surface. The time-varying

surface charge may cause hair oscillation, particularly in some laboratory animals (Tenforde & Kaune, 1987; Tenforde, 1991). Humans can detect 60-Hz electric fields through hair stimulation at about 20 kV/m, while the threshold is lower for some furry rodents (Tenforde, 1991). In contrast, because tissue permeability to magnetic fields is the same as that of free space, these fields penetrate the body with virtually no distortion. The magnitude of the induced electric fields depends mostly on the body size and shape, and the field orientation. The conductivities of various tissues have a lesser influence on the induced electric fields. Extensive data are available on induced electric field and current density values for exposure to ELF electric and magnetic fields, as outlined in detail in section 1.3.2.

A well-established physical mechanism of interaction at the cellular level is the stimulation of excitable cells, such as those in nerves, muscles and the heart which occurs when the electric field in the tissue exceeds a threshold value of V_m (the potential across a cell membrane). Once this threshold is exceeded, the nerve or muscle cell propagates an action potential. The threshold V_m depends on cell type, dimension and shape as well as the signal frequency, duration and waveform (e.g. monopolar pulse, bipolar pulse, sinusoid, single pulse or repeated pulses). Cell excitation and action potential propagation are complex non-linear processes (Plonsey & Barr, 1988; Reilly, 1992; Malmivuo & Plonsey, 1995). A typical value for V_m is 20 mV for the optimal pulse shape, duration and an appropriate polarity causing depolarization (Reilly, 1992, 1998).

To induce neural or cardiac stimulation by 50- or 60-Hz fields, very strong external electric or magnetic fields are required: the reported thresholds are above 1 A/m² (Bailey et al., 1997).

Experimental evidence and thresholds have been determined in human volunteers for magnetic stimulation of the visual system causing phosphenes, which are weak visual sensations (Lövsund et al., 1979, 1980). The lowest threshold magnetic field strength is 8 mT (in darkness) at 20 Hz. The threshold increases for higher and lower frequencies of the magnetic field as well as when the background is illuminated. Phosphenes have also been produced by direct electrostimulation. Again, the threshold was observed for 20 Hz and increases at higher and lower frequencies. It is believed that the effect is a result of the interaction of the induced current with electrically excitable cells in the retina.

The above mechanisms have a well-understood physical basis.

Several other physical interactions have been examined theoretically. Forces exerted by the field on ions and charged molecules have been compared with forces generated by biological structures. For example, an electric field of 5 mV/m in tissue produces a force on a charged molecule of 2×10^{-5} piconewton (pN). In comparison, biological activity reported in various studies is associated with forces above 1 pN, and typically above 10 pN (Valberg et al., 1997).

At ELF, the radical-pair mechanism described above for static magnetic fields still applies. This is because the period of ELF fields, ~ 20 ms, is long compared to the

lifetime of radical pairs (nano- to microseconds). Therefore, the radical pairs experience the instantaneous combined static and ELF magnetic fields.

In addition, a number of other mechanisms have been suggested, for which either the physical basis is not yet clear or the experimental evidence for relevance to the biological effects of ELF fields is still being sought.

From present knowledge, it is clear that there are a number of mechanisms theoretically capable of explaining the occurrence of biological effects at high field strengths. Electric fields induced in tissue are known to produce effects at levels corresponding to an external field of above 0.4 mT and 5–10 kV/m (Bernhardt, 1988).

5. Studies of ELF electric and magnetic fields relevant to carcinogenicity

Studies on the possible carcinogenic effects of ELF electric and magnetic fields are hampered by complications, or lack of information, at almost every level. Issues of EMF exposure which affect the interpretation of referent epidemiological studies are discussed in section 2.1.1. High-quality studies of cancer induced in experimental animals by ELF electric and magnetic fields have been initiated fairly recently. Attempts have been made to examine carcinogenesis associated with exposure to electric and magnetic fields in the context of a multistep process of cancer causation. However, the manner in which these fields might interact with other stimuli, including carcinogens such as X-rays, ultraviolet radiation and chemicals may include as yet undefined processes. Studies of carcinogenesis in experimental animals, and their implications are discussed in section 3.

Studies of the effects of ELF electric and magnetic fields on cells in culture, or using simpler biological systems have attempted to characterize particular molecular processes. Sufficient studies are available to identify other limitations on any simple correlation between 'conventional' carcinogens and the putative hazard under investigation. Firstly, it is apparent that many systems fail to provide any evidence of a treatment-related effect. Secondly, when such effects are observed, other laboratories have often been unable to reproduce the observation. Such failure to reproduce extends across a range of phenomena, and often involves numerous investigators. It is not, therefore, a simple difference between two centres and is unlikely to be explicable simply as the result of a lack of care by one or more of the laboratories concerned, but may be a consequence of an inability to reproduce exactly the electric and magnetic fields to which cells or whole animals have been exposed in a particular study.

The many parameters known to characterize electric and magnetic fields have been outlined above. Most often, an experimental field is described by reference to the intensity alone (usually specified in V/m for electric fields or Tesla for magnetic

fields). Other as yet unspecified characteristics of the field may contribute, if not be critical to, particular experimental results.

6.   References

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