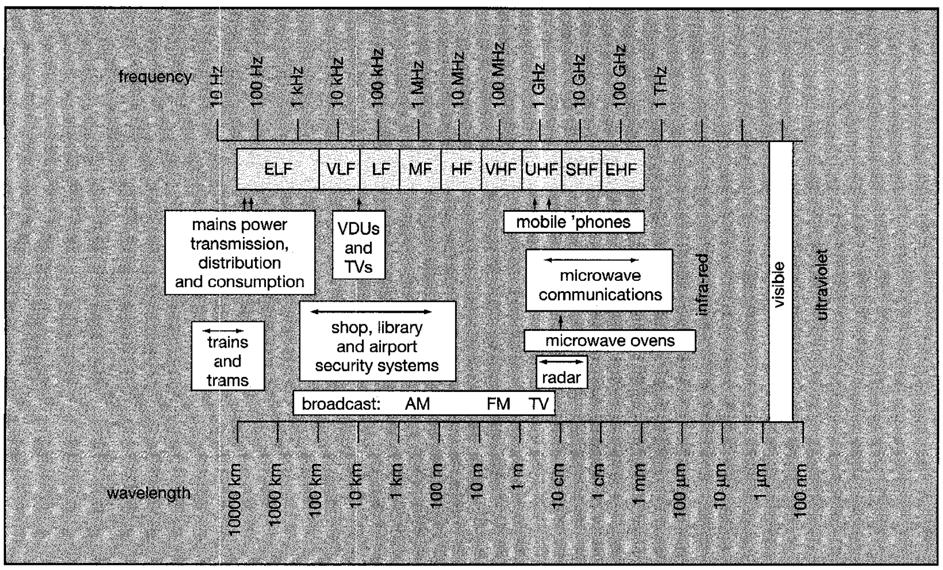
Biological effects of electromagnetic fields

by Zenon Sienkiewicz

There is much concern and controversy surrounding the effects of low-level electromagnetic fields and radiation. After many years of study, a few subtle effects have been seen, but there is still no convincing biological evidence to suggest that exposure to the fields commonly encountered in the environment would cause any significant adverse health effect in humans.

Environmental exposure to man-made electromagnetic fields (EMFs) and radiation has steadily increased throughout this century. This is due to increased demands for the provision and consumption of electricity, advances in technology, and changes in social behaviour. The result is that everyone today is exposed to a complex mix of EMFs, both at home and at work, from the generation and transmission of electricity, from domestic appliances and industrial plant, and from telecommunications and broadcasting (Fig. 1). While there have been many undoubted benefits from the widespread use of electricity, there has been growing concern that exposure to EMFs at even low levels could have detrimental consequences on human health (Table 1). Much of this has arisen as a consequence of epidemiological studies, some of which have purported to demonstrate an association between the incidence of several human cancers and various (indirect) measures of exposure to EMFs; however this evidence is not discussed here.

A large number of laboratory experiments have been performed in response to this concern.[1–4] Much of this research has used rodents or other mammals, although the recent advances in cellular and molecular biology



1 The electromagnetic spectrum. This Figure shows the ITU designated frequency bands and the major sources of exposure to electromagnetic fields

Table 1 Brief history of electromagnetic phenomena and health concerns

1820	Modern awareness of electromagnetism begins: Oersted deflects the needle of a compass using a magnetic field produced by an electric current flowing in a wire.
1831	Michael Faraday publishes famous treatise on electromagnetism.
1873	James Clerk Maxwell brings together ideas on electricity and magnetism into one complete theory.
1880s	First power stations start to generate electricity.
1901	Birth of global radiocommunications: Guglielmo Marconi transmits radio signals from south-western England to Newfoundland.
1920	Regular radio broadcasts begin in the Netherlands and USA. Other countries quickly follow.
1935	Radiolocation system (radar) built by Robert Watson-Watt in Britain. Similar systems under development in Italy and Germany.
1936	Birth of television: BBC begins transmissions in London.
1940	Radiotelegraph system covers the world.
1950s	Growth in domestic electrical appliances.
1960s	Commercial telecommunication satellites developed. Concerns regarding effects of electromagnetic fields on health.
1976	Start of clinical magnetic resonance imaging.
1979	First concerns about overhead power lines and cancer following publication of paper by Wertheimer and Leeper.
1980s	Widespread use of computers in commerce and industry. Concerns about computer screens and miscarriage.
1990s	Rapid expansion in personal mobile telecommunications. Concerns about cancer from mobile telephones.

have resulted in the increasing use of cell cultures[5]. Relatively few studies have used human volunteers. Many biological endpoints have been examined using various frequencies and a mixture of field strengths. However, neither a consistent nor a coherent strategy has been adopted in this endeavour, which has resulted in an extensive and diverse literature that contains many isolated and uncorroborated observations, and there have been few attempts to replicate important or controversial studies.[1,6] Overall, very few effects of exposure have been established firmly.

The biological effects are discussed here in two separate sections, as the interactions of electromagnetic fields with biological tissues differ in different regions of the spectrum. The first section considers exposure to time-varying electric and magnetic fields with frequencies less than 100 kHz, and the second considers exposure to microwave and radio-frequency radiation with frequencies between 100 kHz and 300 GHz. In each case the established interaction mechanisms and known effects are considered first, and this is followed by a brief discussion of possible effects in specific areas which have generated particular interest or concern.

Time-varying electric and magnetic fields with frequencies less than 100 kHz

The physical interaction of time-varying electric and magnetic fields with living material results in the induction of electric fields and currents in biological tissues (Figs. 2 and 3). The magnitudes of these effects are determined by a complex interplay between many factors, including the frequency and intensity of the field, the electrical properties of the tissues involved and the exposure conditions.

If the fields are sufficiently intense, stimulation of nerves and muscles within the body will occur, while lower intensities may cause modulation of activity within the brain and nervous system.[3,7] Magnetic field pulses, for example, have been used to stimulate nerves in a number of clinical studies, and magnetic phosphenes (flickering, elusive images perceived in the periphery of vision) are caused by field-induced currents affecting the normal electrical activity of the retina in the eye. Fields capable of generating phosphenes are unlikely to be encountered except in a very few occupational situations. The currents induced by the fields usually encountered in the environment will be less than or comparable to the natural currents in the tissues as a result of normal nervous and muscular activities.

It is also well established that electric fields in air induce alternating electric charges on the surface of an exposed body. This can cause noticeable vibration of the hairs on the limbs and trunk. The threshold for perception of hair vibration in humans shows wide individual variation, and occurs in ten percent of adults exposed to a 50 Hz field at about 12 kV m^{-1}, and in five percent of those exposed at about 3 kV m^{-1}, a level that can be found under overhead power lines. This effect is not considered hazardous but may become stressful if exposure is prolonged. The threshold for annoyance for most people is reported to be between 15 and 20 kV m^{-1}.

A number of other biophysical interaction mechanisms have been proposed to explain how low-intensity fields could affect living tissues and exert biological effects. These mechanisms include ion-cyclotron resonance, parametric resonance, and direct field-effects on magnetite particles in brain cells. Some of these enjoy limited experimental support, but there are theoretical reasons to suggest that such mechanisms would not cause significant biological effects.

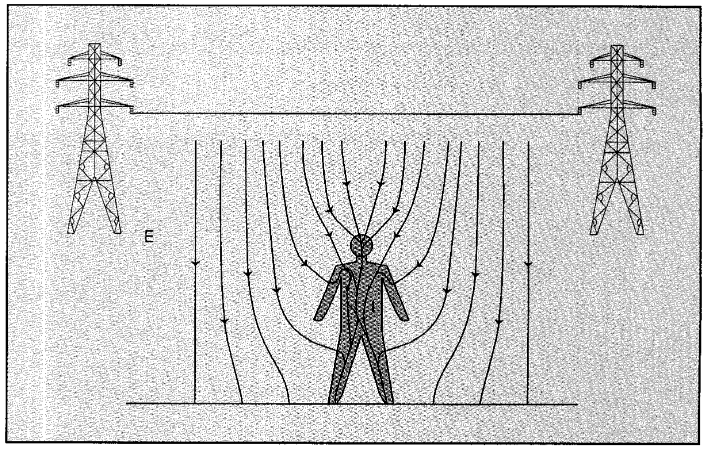
The restrictions on human exposure to low-frequency electric and magnetic fields formulated by the National Radiological Protection Board (NRPB)[8] are based on limiting the induced current density in the body to avoid the possibility of subtle effects on the functions of the brain and nervous system, and also on avoiding the perception of surface charge in electric fields.

Physiological and behavioural effects

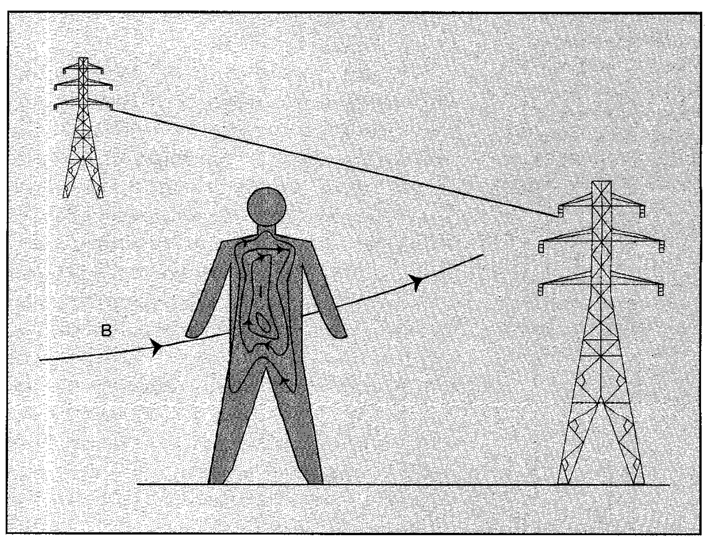
The electric fields and currents induced in biological tissues by low-frequency fields could result in a variety of physiological or psychological responses. There is little evidence, however, to suggest that low-level exposure causes any consistent effect on most physiological endpoints, and the majority of studies have reported negative results using a variety of field conditions. Some parameters were sometimes found altered, although many of these still fell within the normal range of variation, and others appeared to be without functional significance.[2,3,7]

The most frequently observed effects of exposure relate to subtle effects on the brain and central nervous system. Changes in arousal and complex reasoning in volunteers have been reported for exposure at levels that could be encountered under high-voltage power lines, and this appears consistent with modulation of the normal information processing mechanisms in the brain caused by field-induced electric currents. Short-term changes in learning and memory have also been seen in rodents exposed to magnetic fields at levels that may be found in a few occupational settings (Fig. 4). A variety of other responses have been reported in animals and *in vitro* preparations, including modification of neuronal activity, changes in neurotransmitter metabolism, attenuation of endogenous opioid and opiate-mediated responses, and interference with the normal mechanisms of calcium ion homeostasis. The significance of most of these responses is not clear.[2,6]

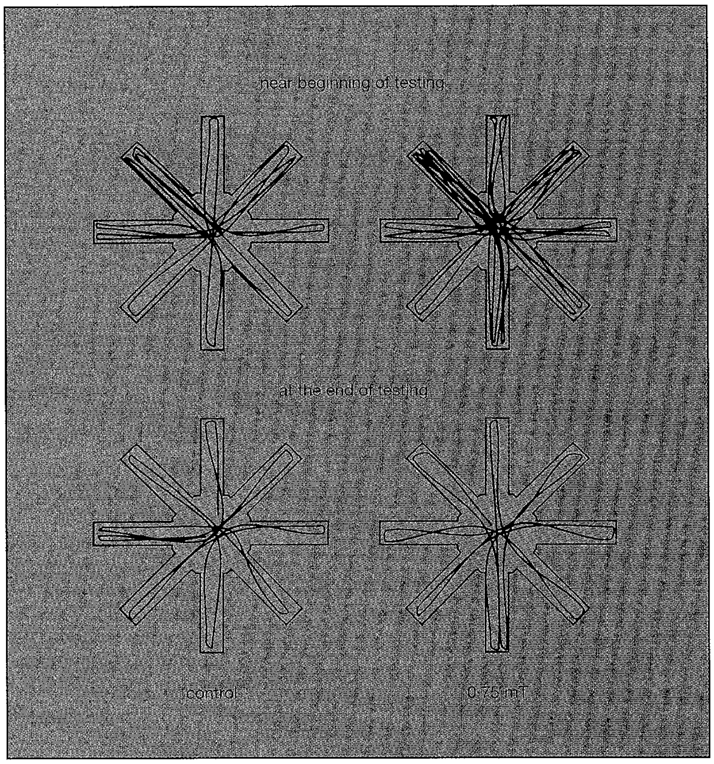
In addition, a few effects have been reported in volunteers under specific conditions, but none is well established.[2,6,7] Acute exposure to an electric field of 9 kV m^{-1} and a magnetic field of 20 μT may slightly reduce resting heart rate (by a few beats per minute). The same exposure may also cause specific changes in the electroencephalogram consistent with impairment in the cognitive processes involved in decision making. The changes in heart rate were reduced if the subjects were mentally alert or following fairly hard exercise when the heart rate was elevated. The exposure history of the subject within the experiment also appeared to affect the magnitude of the observed effect. Neither of these effects caused any obvious functional impairment, however, and all changes appear well within the normal range. It is also possible that under special



2 Electric currents induced within a body exposed to an alternating electric field. Currents flow to and from ground through the tissues. Surface electric charges on the body may induce perceptible hair vibration



3 Currents induced in a body exposed to an alternating magnetic field. Currents circulate within the body, not necessarily to ground



4 Diagram illustrating the behaviour of adult mice during particular testing sessions in a radial arm maze. The paths taken by individual animals are shown. In this experiment, the animals learn to forage for food placed at the end of each arm of the maze. Animals which were exposed to a 50 Hz magnetic field at 0·75 mT immediately before each session (right) performed very poorly at first and kept making mistakes by re-entering previously visited arms. However, these effects were transitory and the exposed animals finally performed as well as the unexposed, control animals (Data from the author's own laboratory)

circumstances exposure to very weak electric fields may influence circadian rhythms, but it is most unlikely that this effect could occur under normal, everyday conditions. The effect has been demonstrated only in volunteers exposed to a 10 Hz electric field at 2·5 V m^{-1} who were living in an underground apartment without access to normal temporal signals such as light/dark intervals or social interactions. Even under these artificial conditions, the electric field was only about half as effective a signal as a light/dark cycle.

Chronic exposure to electric fields has been reported to affect a variety of circadian rhythms in animals, including that for the synthesis and release of melatonin, a hormone secreted by the pineal gland mainly at night. This latter possibility has generated wide interest because changes in melatonin have been implicated in the aetiology of some cancers, and it has been speculated that such changes could be a route whereby exposure might contribute towards an increased risk of cancer. The original experiments[2,7] described reductions in the normal nocturnal peak of melatonin in rats following long-term exposure to electric fields above a threshold of about 2 kV m^{-1}. Later studies suggested that magnetic fields may also disrupt melatonin rhythms in animals. However, more recent studies have not always reported obvious field-dependent effects in a variety of animals, and experiments with either non-human primates or volunteers have failed to find any consistent effect on melatonin levels. This suggests that any link between exposure to low-frequency fields and depression of nocturnal melatonin levels must remain highly tentative.[9]

There is very little information on the effects of exposure to fields well above those generally encountered by members of the public, although headaches and alterations in the visual evoked potential response have been reported in volunteers with acute exposure to magnetic fields above 60 mT. The latter persisted even after the field was terminated. However, visual acuity was not affected, and there were no effects on a number of other physiological parameters.

Reproduction and development

Particular concern has been expressed about the possible adverse effects of occupational exposure to low-frequency fields on the development of the embryo and foetus, particularly by operators of visual display units (VDUs) and by staff operating clinical magnetic resonance diagnostic systems. However, there is little epidemiological evidence for any adverse effect on pregnancy outcome from VDU use.[10] Interest was first aroused by reports of malformations in developing chick embryos exposed to pulsed magnetic fields at about 1 μT. A large number of studies have investigated this possibility using a variety of frequencies, waveforms and exposure conditions. The overall results of this research are somewhat ambiguous, with some studies reporting malfunctions and delayed development, and many others failing to find any effects.

The relevance for humans of studies using chick embryos is uncertain, and studies on mammalian development should be more applicable to humans. A number of studies have been performed using mammals, and most of these have failed to find any consistent effects on fertility and reproductive performance, or on embryonic, foetal and postnatal development. The few positive effects that have been reported tend not to be consistent between studies. It is possible, however, that chronic prenatal exposure to intense fields, well above the levels that would be normally encountered, may cause transient retardation in development and possibly induce subtle behavioural deficits in adults, although there are too few data to make explicit conclusions. Taken together, these animal studies offer no support to the possibility that spontaneous abortion, congenital malformation or other developmental defects would be increased in women exposed to sources of electric and magnetic fields (such as VDUs) during pregnancy.[2,10]

Cancer-related studies

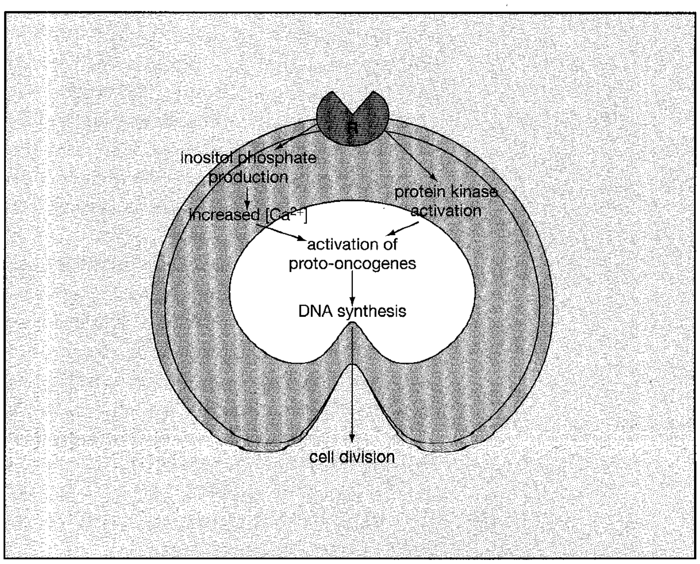
The major concern in recent years has been the possibility that low-intensity electric and magnetic fields may influence the development of cancers.[11] Carcinogenesis is generally believed to involve at least three stages: initiation, involving genetic mutation of one or more cells; promotion, involving multiplication and accumulation of damaged cells; and progression, the accumulation of further genetic abnormalities resulting in increased malignancy. There is no convincing evidence that low-intensity fields cause genetic damage, and, unlike ionising radiation, EMFs possess insufficient energy to damage DNA directly. It is therefore extremely unlikely that they could have any effect on the initiation of cancer.[12]

It is generally accepted that if low-frequency fields do affect carcinogenesis it is likely to be only at the level of promotion. This has been investigated at the cellular and molecular level by looking for possible effects at the various stages in the cell signalling pathways that lead to cell division: an appropriate stimulus received at the cell membrane will cause a hierarchical cascade of biochemical responses that eventually result in division of the cell, and low-frequency fields could affect any of the steps in these pathways (Fig. 5). Most tumour-promoting chemicals act to stimulate cell proliferation, whilst increased proliferation in itself may cause tumours via increases in mutation rate.

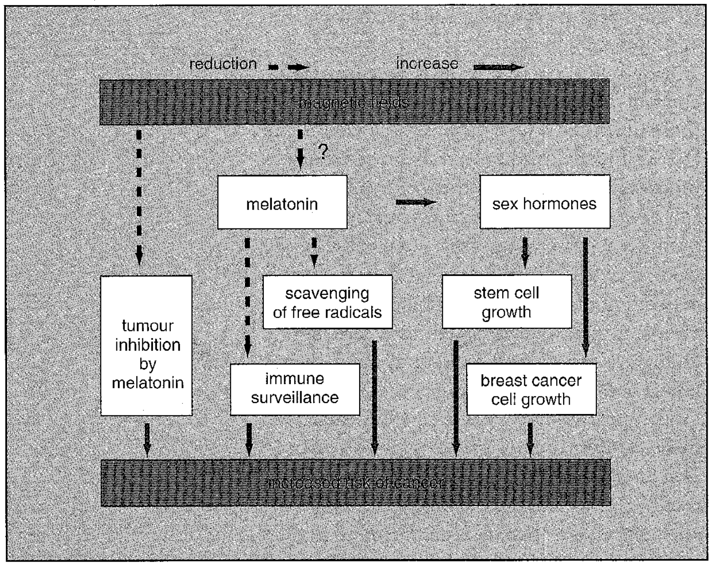
It is clear that magnetic fields at environmental levels have no effects on the early stages of the signalling pathways, although fields above 100–200 μT may lead to activation of certain enzyme systems and increased production of specific messenger molecules, including calcium ions.[2,12] Other studies have followed the signalling pathways to the nucleus and examined the expression of genes associated with cancer. There is no consistent evidence that fields below about 100 μT have any effect on signalling pathways, but very intense fields (at about 20 mT) may enhance gene expression. However, even these changes tend to be very small compared to those produced by other agents, such as growth factors. Further studies have measured the rates of proliferation in cultures of field-exposed cells. No sustained proliferative responses have been seen even using very intense fields (20 mT). This tends to suggest that the small field-dependent changes seen in some of the earlier events of the signalling pathway are not of biological significance, and they may simply reflect some transient, non-specific response.[12]

The potential for low-frequency magnetic fields to affect tumour promotion has also been examined directly using animal carcinogenesis models.[9] Here animals are exposed following application of a chemical carcinogen to initiate the tumours. Magnetic fields do not have any effect on the development of skin tumours and although the experimental evidence is contentious, some effect on breast cancer is possible. Replicate studies are underway which will help to resolve this uncertainty. There is also some evidence from both animal and cellular studies to suggest that low-frequency magnetic fields may act as co-promoters, essentially enhancing the effects of chemical tumour promoters. However, these effects have not been confirmed in replicate studies, therefore no firm conclusions can be drawn.

The few studies that have investigated whether low-frequency fields affect tumour progression are not suggestive of any significant effects. It has been proposed that magnetic



5 Simplified diagram of signal transduction pathways within a cell. An appropriate stimulus received at the receptor (R) in the cell membrane causes a cascade of biochemical responses that cause DNA synthesis and ultimately cell division



6 Possible means whereby magnetic fields have been considered to influence the risk of cancers. Perhaps the weakest link in this chain of responses is the crucial one: are night-time melatonin levels reduced by exposure to magnetic fields? If this link does not occur, nearly all of the other responses become moot

fields could affect tumour progression by inhibition of the night-time synthesis of melatonin (Fig. 6), which is believed to be a natural inhibitor of certain tumours. Some studies[9] suggest that magnetic fields may reduce the inhibitory effects of melatonin on the growth of breast cancer cells in culture, but the magnitude of this effect was relatively small: magnetic fields alone did not affect cell growth.

Radio-frequency radiation at frequencies between 100 kHz and 300 GHz

Microwave and radio-frequency (RF) radiation have been used for many years in a wide range of applications. These include broadcasting, telecommunications and radar; and microwave and RF radiation are also widely used in industry for sealing, drying and curing dielectric materials. Further, RF radiation is used in security and surveillance equipment, and has medical uses such as diathermy and magnetic resonance imaging. Microwave ovens commonly use 2·45 GHz radiation to defrost and cook food.

While there have been many benefits from the use of RF radiation, concern has been expressed that long-term exposure to even low levels could have detrimental consequences on human health. The recent increase in personal communications in particular has heightened public awareness of RF radiation, and rumours have begun circulating that the radiation from mobile telephone handsets and base stations was responsible for causing headaches or even brain tumours and other cancers.

Many experiments[3,13,14] have been performed with microwave and RF radiation over the last 30 years or so, although interest declined to a large extent in the 1980s as attention focused on the effects of power frequency fields. Much of the older research investigated the effects of 2·45 GHz radiation on rodents and other mammals, while some of the more recent studies have concentrated on elucidating possible mechanisms at the cellular level. Increasingly, these studies are using the frequencies associated with mobile telephony (around 900 MHz and 1·8 GHz). As with low-frequency fields, human volunteer studies are not common. Many biological endpoints have been examined using various exposure conditions, but, as with low-frequency fields, very few effects have been found.

It is well established that as the frequency increases from about 100 kHz the dominant effect of exposure of biological tissues becomes heating. The photon energy of RF radiation is too small to affect chemical bonding directly: even at 300 GHz, which is the border between RF and infra-red radiation, the photon energy is only about 10^{-3} eV and this decreases linearly with decreasing frequency. Covalent bond disruption has an activation energy of 5 eV and even hydrogen bond disruption has an activation energy of 10^{-1} eV. The electric fields induced in tissues by RF radiation result in energy absorption due to the polarisation of electrically charged structures and the flow of ions. It is assumed that the increase in linear and rotational energy is rapidly dissipated by molecular collision, resulting in generalised heating.

The vast majority of the reported physiological, behavioural and developmental effects of exposure to RF radiation are consistent with responses to induced heating, resulting either in responses to rises in tissue or body temperature of about 1°C or more, or in responses for minimising the total heat load.[4,13] These responses show clearly defined thresholds below which consistent effects do not occur. The total heat load experienced during RF exposure is the sum of the specific energy absorption rate (SAR) and the endogenous rate of heat production; the latter ranges from about 1 W kg^{-1} at rest to about 10 W kg^{-1} during short periods of hard exercise.

Power deposition within the body from RF radiation is never uniform: differences in the electrical properties of tissues and the reflection and refraction of radiation at the interfaces of these tissues can result in very inhomogeneous patterns of energy deposition (Fig. 7).

Differences in blood perfusion rates in different tissues will be a determinant of how effectively any absorbed energy is dissipated. Tissues like the eyes and testes, which are known to be sensitive to heat, are also considered sensitive to the heating effects of RF radiation. In addition, heat is an established teratogen, and the embryo and foetus may be particularly sensitive to RF-induced heating, since heat exchange across the placenta will be less effective than heat loss to the environment. The severity of any teratologic effect appears dependent on the maternal temperature. The magnitude of all these effects is dependent on field strength, and will be insignificant at exposures experienced by the majority of the population.

The restrictions on human exposure to RF radiation recommended by NRPB[8] are based on the limitation of whole body heating and the preferential heating of small volumes of tissue. The absorption of RF radiation can be detected by temperature sensitive receptors in the skin, although this may not provide a reliable mechanism of protection against possible harmful exposure.

Amplitude-modulated field effects

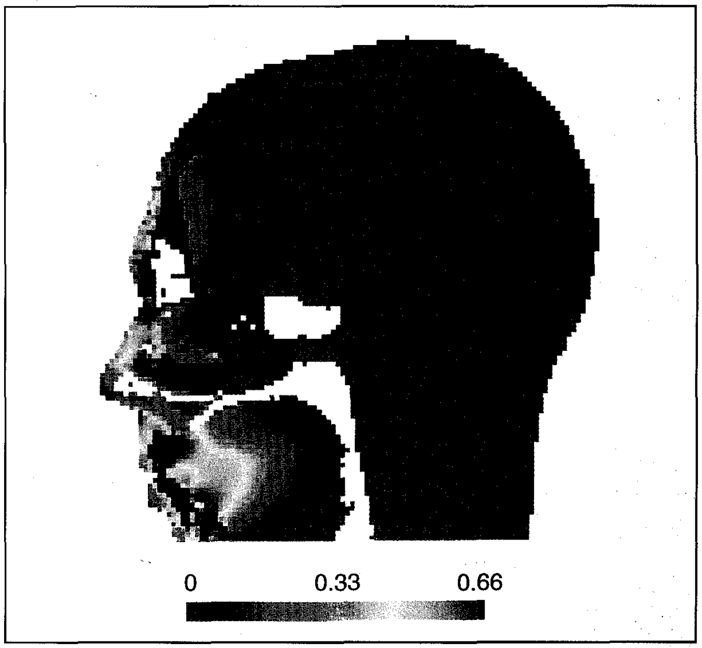
A number of effects have been reported with amplitude-modulated fields which do not appear to be based on the thermal responses to RF radiation.[14] The functional significance of these effects is not clear. For example, changes in calcium ion mobility in brain tissues and alterations in the electrical activity in the brain have sometimes been reported with exposure to low-level microwaves modulated at specific frequencies (often 16 Hz). Other studies have reported intracellular changes in regulatory enzymes. It is difficult to gauge the importance of these results since the effects not only tend to be small in magnitude and transient in duration, but also depend upon the exposure parameters, the biological system used, and the endpoints examined.

Pulsed-field effects

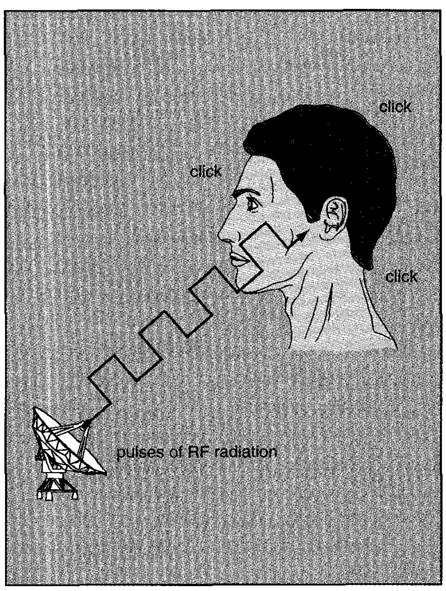
In recent years much interest has been expressed in the biological effects of pulse-modulated RF radiation, and exposure has been reported to produce a number of behavioural and perhaps ocular responses.[4,6]

It is possible to hear microwaves (Fig. 8). Humans can perceive pulse-modulated RF radiation between 200 MHz and 6·5 GHz as a buzzing, clicking, hissing or popping noise, depending on the modulation characteristics of the field. The effect is generally attributed[4] to thermoelastic expansion of brain tissue, following the small but rapid increase in temperature on the absorption of the incident energy, generating a sound wave in the head which stimulates the cochlea. Repeated or prolonged exposure to these auditory effects is considered stressful.

Acute exposure to pulsed microwaves



7 Predicted energy deposition patterns in a head exposed to the fields associated with using a mobile telephone handset. The scale indicates energy in watts per kilogram per watt of output power [Courtesy of Dr. P. J. Dimbylow]



8 Microwave hearing phenomenon. Some individuals can perceive pulsed microwaves as a popping, hissing or clicking noise

appears to cause a stress-like effect on brain neurochemistry and may cause learning deficits in rats. Exposure to high-peak-power microwave pulses appears to cause specific behavioural responses, including suppression of the acoustic startle response, and, with very intense pulses, the induction of involuntary body movements. It is possible that the latter effects may be related to the microwave hearing phenomena, as the specific absorption per pulse was far in excess of the auditory threshold.[6] These effects with pulsed fields, however, are not expected in people at the levels of exposure commonly encountered.

Specific ocular effects may also occur but the data are contradictory. Degenerative changes have been found in various tissues of the eye, including the lens and retina, following protracted exposures to pulsed microwaves at levels which did not induce significant heating. These effects were exacerbated by pretreatment of the eye with the ophthalmic drug timolol maleate. However, these findings could not be replicated by an independent laboratory which casts doubt on their generality.

Cancer-related studies

Public concern about the possible carcinogenicity of RF radiation may be growing with the widespread and increasing use of mobile communication devices. Most experiments to date have used the microwave frequency of 2·45 GHz and not the common frequencies used in mobile telephony, but it is clear that all RF radiation lacks sufficient energy to disrupt covalent bonds directly, and so there is no theoretical basis to suggest that it could adversely affect the integrity of DNA. There is a large body of experimental evidence confirming that exposure to RF radiation does not increase mutation or chromosome aberration frequencies when temperatures are maintained within physiological limits. RF radiation is thus not considered to act as an initiator of carcinogenesis.[9]

There is limited evidence indicating that RF radiation may affect cell growth and proliferation, possibly through effects on cell signalling. This might provide a mechanism through which RF fields could influence tumour promotion, although there is little evidence for this as yet. The possible effects on gene expression have not been thoroughly investigated, and the few positive effects reported could be due to thermal effects.

It has also been suggested that RF radiation may affect tumour progression, and one mechanism for this could involve impairment of the immune system, which can play a role in preventing tumour development. However, the ability of RF radiation to affect tumour progression is equivocal, and no clearly defined effects can be seen. There are some interesting data from an *in vitro* transformation system using cells with abnormal numbers of chromosomes which indicate that exposure to RF radiation may induce dose-dependent latent damage which can only be revealed by the concurrent action of a chemical promoter.[13] The relevance of these results to normal human cells is questionable, and replication using cultures of normal cells is required before any definite conclusions can be drawn.

A recent study using transgenic (genetically manipulated) mice prone to the development of lymphomas has attracted much publicity. This study revealed that the number of tumours in animals exposed to RF radiation typical of mobile telephone systems was about double that expected in unexposed animals. However, the implications of this result for humans are far from clear, and it is very difficult to extrapolate the results to non-transgenic animals, yet alone to humans.

Much publicity has also followed reports that exposure to microwave radiation may disrupt the integrity of DNA molecules in brain cells and cause an increase in single and double strand breaks. This has sometimes been interpreted as suggesting some increased risk of cancer. However, there are some internal inconsistencies in these data and, once again, attempts to replicate these results by independent laboratories have not been successful. It is possible that the observed effects may reflect subtle changes in DNA repair kinetics or other aspects of DNA metabolism caused by stresses associated with exposure.

Summary

After many years of research and much effort, very few biological effects can be unequivocally attributed to exposure to low-intensity EMFs. There is no categorical evidence to suggest that exposure at the levels commonly found in the environment causes any significant long-term or pathological effect. In contrast, much folklore suggests that electricity and magnetism can affect people in strange and powerful ways;

therapies using magnets are commonplace in many parts of the world; and bizarre and outré events often attract explanations based on the supposed effects of electromagnetic fields. As with other environmental health issues, much of the general public may have an incomplete or even confused understanding of electromagnetic phenomena, while a minority, perhaps living close to obvious sources of exposure (such as overhead power lines or mobile telephone base stations) may have very strong opinions about health effects.

There is much argument and debate surrounding the effects of exposure to low-frequency electric and magnetic fields. Apart from the well established perceptual effects, a few subtle responses have been observed, but most of these appear unlikely to have any definite health consequences and many appear small in magnitude and well within the limits of normal biological regulation. In particular, there is no convincing or consistent evidence to suggest that exposure to low-intensity fields causes any adverse physiological response, is responsible for any serious developmental defect in mammals, or is able to influence significantly any of the accepted stages of carcinogenesis.

The heating effects of RF radiation are well established and the vast majority of the reported biological effects of exposure to RF radiation are consistent with the absorption of heat. The magnitude of these effects is dependent on field strength and will be significant at exposures experienced by the majority of the population. Effects in the absence of heating are controversial and have not been established firmly, although pulsed RF radiation may cause specific behavioural effects, possibly as a consequence of audition of the field.

Overall, biological effects resulting from exposure to EMFs at levels normally encountered by members of the public have a tendency to be small in magnitude, short in duration and reversible. Effects may also be seen only under very specific exposure and test conditions. This suggests any risk to health, if it exists, would be small. It is possible to believe that the fear of EMFs is far greater than any effect from EMFs.

Nevertheless, public concern remains high, and research is continuing to determine more clearly what effects are possible and to define better the conditions under which these effects can be observed.

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