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Health Effects from Radiofrequency Electromagnetic Fields

Report of an independent Advisory Group on Non-ionising Radiation

National Radiological Protection Board

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Working in partnership with the Health Protection Agency

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HEALTH EFFECTS FROM RADIOFREQUENCY ELECTROMAGNETIC FIELDS

Report of an independent Advisory Group on Non-ionising Radiation

CHAIRMAN: PROFESSOR A J SWERDLOW

This report from the Advisory Group on Non-ionising Radiation reflects understanding and evaluation of the current scientific evidence as presented and referenced in this document.

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1 Introduction

1 People are exposed to many sources of radiofrequency (RF) electromagnetic fields including radio and TV transmitters, telecommunications links and satellite communications as well as mobile phones and their supporting transmitters (base stations). The use of mobile phones has increased considerably in recent years and has come to be seen as an essential means of communication in commerce and society. There are now over 50 million mobile phones in use in the UK supported by about 35 000 base stations. The number of phones reflects the need that people see for this technology; there have, however, been concerns expressed about possible health effects associated with exposure to RF fields from the phones and their base stations.

2 In April 1999, the then Minister for Public Health, Tessa Jowell, announced the formation of an Independent Expert Group on Mobile Phones (IEGMP) that she had asked the Chairman of NRPB to set up. Sir William Stewart FRS FRSE was the Chairman of IEGMP and its remit was:

> **'To consider present concerns about the possible health effects from the use of mobile phones, base stations and transmitters. To conduct a rigorous assessment of existing research and to give advice based on the present state of knowledge. To make recommendations on further work that should be carried out to improve the basis for sound advice.'**

3 Membership of IEGMP was announced in August 1999 and its report on mobile phones and health was issued in May 2000 (IEGMP, 2000). The report provided a comprehensive review of experimental and epidemiological studies related to exposures to RF radiation and made a number of recommendations. These covered government and industry, research requirements, the need for better public information and consumer choice, and the role of NRPB. These recommendations have now been taken forward by government and other bodies.

4 In relation to possible health effects, IEGMP concluded that:

> **'the balance of evidence to date suggests that exposures to RF radiation below NRPB and ICNIRP guidelines do not cause adverse health effects to the general population' (paragraph 1.17).**

5 IEGMP noted, however, that there is some scientific evidence to suggest that there might be biological effects occurring at exposures below these guidelines. It was not possible to say that exposures to RF radiation, even at levels below national guidelines, are totally without potential adverse health effects. It was concluded that the gaps in knowledge were sufficient to justify a precautionary approach to the development of this technology and recommendations were made for further research. A comprehensive UK Mobile Telecommunications and Health Research (MTHR) programme has now been established under an independent Programme Management Committee (PMC).

6 IEGMP additionally recommended that:

> **'the issue of possible health effects from mobile phone technology should be the subject of a further review in three years time, or earlier if circumstances demand it' (paragraph 1.60).**

7 In responding to the recommendations in the report, the government asked the Board of NRPB to undertake this further review and the Board requested its independent Advisory Group on Non-ionising Radiation (AGNIR) to carry this out.

8 The Advisory Group provides support for the development of NRPB advice on non-ionising radiation. It was set up by the Director of NRPB in 1990 with terms of reference:

> **'to review work on the biological effects of non-ionising radiation relevant to human health and to advise on research priorities'**

9 The Advisory Group was reconstituted in 1999 as an independent body that now reports directly to the Board of NRPB. To date, it has issued reports covering exposures both to electromagnetic fields and ultraviolet radiation. Two principal reports have been issued that relate to exposures to electric and magnetic fields and the risk of cancer (AGNIR, 1992, 2001a). The emphasis of both these reports has been on the consequences of exposure to power frequencies (50 Hz in the UK). A number of supplementary reports and statements have also been issued (AGNIR, 1993, 1994a) together with reports on visual display units (VDUs) (AGNIR, 1994b) and on extremely low frequency electromagnetic fields and neurodegenerative disease (AGNIR, 2001b). In addition, a report has been issued on possible health effects from terrestrial trunked radio (TETRA) (AGNIR, 2001b), a radio communication system developed mainly for use by the emergency services (see paragraph 15).

10 In addition to the IEGMP report a number of other reviews have been issued by national bodies that have been concerned with possible effects on health of exposures to RF fields from mobile phones and base stations. These include a review of research needs by a European Commission Expert Group (1996), a review by an Expert Panel of the Royal Society of Canada (1999), the Zmirou Report for Health France (2001), reviews of both base stations and mobile phones for the Health Council of the Netherlands (2000, 2002), an interim report by the British Medical Association on mobile phones and health (2001) and a French Senate Report (OPECTS, 2003).

11 The present report is the first by the Advisory Group to have comprehensively addressed scientific research related to concerns about exposures to RF fields. The Advisory Group considered that this report should cover sources of RF exposure as well as experimental and epidemiological studies relevant to concerns about human health. The RF fields to which people may be exposed from a variety of devices cover a wide range with very variable signal characteristics and these are considered. The report is limited, however, to radiation effects, and does not consider other aspects of mobile phone or other RF device use.

12 For instance, the review by IEGMP (2000) concluded that the use of mobile phones whilst driving distracts drivers and has a detrimental effect on their response. This translated into a substantially increased risk of an accident and the evidence suggested that the negative effects of phone use while driving were similar whether the phone was handheld or hands-free. The present report does not cover this effect of the use of mobile phones because it appears not to be an effect on body tissues of RF exposure. Furthermore, the report does not give advice on the exposure of patients carried out under medical supervision as part of treatment or examination, nor is it concerned with possible interference with medical devices.

13 The sources of RF fields to which people may be exposed are many and varied. Within the frequency band from 3 kHz to 300 GHz the sources include those used for telecommunications or security and access control where the transmitted fields are essential to their function, and industrial processing such as induction and dielectric heating where the emitted fields are incidental. Communications equipment covers most of the frequency range with TV and radio transmissions frequencies from about 200 kHz to 900 MHz. Personal telecommunication devices operate over the range of frequencies from 100 MHz to 3 GHz with current GSM mobile phones operating at approximately 900 MHz and 1.8 GHz. The next and subsequent generations of mobile telephony will operate at frequencies up to a few GHz. Terrestrial trunked radio (TETRA), used principally by the emergency services, operates around 400 MHz.

14 Many other sources employed in industry operate using the industrial, scientific and medical (ISM) allocated frequencies. Examples are plasma etchers or RF sputtering devices operating at 13.56 MHz, RF PVC welding machines at 27.12 MHz and microwave ovens at 2.45 GHz. RF induction heating equipment operates over the frequency range from about 0.3 to 3 MHz. Radiofrequency security and identification devices have become prevalent in public places and are used over the frequency range from several hundred kHz to several GHz. Military and civil radar systems operate over frequencies from about 0.5 to 10 GHz and line-of-sight 'microwave dishes' employ frequencies that extend into the tens of GHz. The wireless office is now becoming a reality with the introduction of wireless local area network (LAN) systems, which currently operate at 2.45 and 5 GHz, and with new systems continuing to be developed.

15 The IEGMP (2000) report provided some information on TETRA and noted some contradictory results when examining the biological effects of RF emissions pulsed at or near a frequency of 16 Hz (TETRA has a frame rate of 17.6 Hz). While no obvious health effect was suggested it did recommend a precautionary approach. Following a request to NRPB by the Home Office, the issue of possible health effects caused by signals from TETRA sources was comprehensively addressed in a report by the Advisory Group (AGNIR, 2001c). The report noted that the signals from TETRA base stations are not pulsed, whereas those from the mobile terminals (handsets) and repeaters (mounted on vehicles) are pulsed. There is, therefore, no reason to believe that signals from TETRA base stations should be treated differently to those from other base stations. The report also concluded that, although areas of uncertainty remain about the biological effects of low level RF fields in general, include modulated signals, current evidence suggested that it was unlikely that the special features of the signals from TETRA handsets and repeaters posed a hazard to health. The report made a number of recommendations for further research and these are now being taken forward by the MTHR programme and the Home Office. The advice given by the Advisory Group on TETRA is not repeated here.

16 In 1993, NRPB issued guidelines on limiting exposure to electromagnetic fields in the frequency range 0–300 GHz (NRPB, 1993), including RF. These guidelines gave advice on exposure restrictions for both workers who are occupationally exposed and members of the public. In April 1998, the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 1998) published revised guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields in the frequency range up

to 300 Hz. Both the NRPB and ICNIRP guidelines refer to exposures and not to specific sources. The ICNIRP guidelines are explained in Appendix B.

17 Chapter 2 of this report examines the sources and frequency range of various RF sources of 3 Hz and above. It considers the types of systems available and their characteristics. Figure 2.1 illustrates some common RF sources and their operating frequencies. The International Telecommunications Union (ITU) band designations are also shown. Exposures related to various sources of RF fields are compared, where possible, with the ICNIRP guidelines. The chapter also reviews recent information on exposures arising from base stations and mobile phones and summarises available information on exposures from other RF sources, including extensive recent measurements made by NRPB and the Radiocommunications Agency.

18 For an examination of the possible effects on health of RF exposure, experimental work covering human volunteer studies, animal experiments and effects on cells in culture, can all be informative. They are able to provide information on possible health effects that may occur as a consequence of human exposure and on any mechanisms of interaction of RF fields with the cells and tissues of the body. The IEGMP (2000) report comprehensively reviewed the literature on experimental studies. It concluded that experimental studies on cells and animals did not suggest that mobile phone exposures below guideline levels had damaging effects on the heart, blood, the immune system or on reproduction and development. Chapters 3 and 4 of this report examine experimental cellular and animal studies relevant to understanding any biological effects of exposure to RF fields. These chapters mainly examine studies published since the IEGMP report. They do not describe in detail the studies examined by IEGMP, although some of the data obtained from those studies are summarised in tabular form.

19 The IEGMP report noted that there was evidence from volunteer studies that exposure to mobile phone signals at intensities within existing ICNIRP guidelines had direct short-term effects on the electrical activity of the human brain and on cognitive function. These could have their origin in a variety of biological phenomena for which there is some evidence from experiments on isolated cells and animals. IEGMP concluded there was a need to establish whether these direct effects on the brain have consequences for health because, if so and if a threshold could be defined, then exposure guidelines would have to be reconsidered. It was also important to determine whether these effects were caused by local elevation of temperature or by some other 'non-thermal' mechanism. Studies on the effects of mobile phone signals on human brain activity and cognitive function published since completion of the IEGMP report are reviewed in Chapter 5.

20 There have been a number of published reports of health effects of exposure to RF fields at levels significantly above guideline levels. These have mainly arisen in circumstances where people have been working in close proximity to RF sources, including radar antennas, various transmitters and generators, although they have also been found in patients exposed as a result of medical diagnostic procedures and treatments. Health effects noted as a result of exposures above guideline levels were not specifically addressed in the IEGMP report. Some work published prior to 2000 is therefore examined in Chapter 6 together with more recent studies. The relation of various disorders to exposure to RF fields from VDUs has been previously considered by the Advisory Group (AGNIR, 1994b) and is also mentioned briefly.

21 Epidemiological studies provide the most direct information on possible effects on health of exposure to a potentially hazardous agent. At the time of the review by IEGMP, few studies had examined the relationship of mobile phone use to morbidity or mortality, and none had explored the effects of exposure to RF fields from base stations. However, some information was available regarding exposures to other RF sources – for example, in radar and radio operators and from residence near broadcasting towers and masts. The epidemiological evidence on effects of RF exposure from a range of sources did not suggest that such exposures cause cancer. This conclusion was considered to be compatible with the balance of biological evidence, which suggested that RF exposures below guidelines do not cause mutation or initiate or promote tumour formation. However, mobile phones have not been used for long enough to allow comprehensive epidemiological assessment of their impact on health and the Advisory Group decided it could not, at that stage, exclude the possibility of some association between mobile phone technology and cancer.

22 Since publication of the IEGMP report, a number of additional epidemiological studies have been published that have examined possible associations between exposure to RF fields from mobile phones and cancer. These and other epidemiological studies concerned with a possible risk of cancer resulting from RF exposure are reviewed in Chapter 7. For the literature on sources other than mobile phones, the chapter concentrates on new studies published since the IEGMP report, with only a brief review of earlier publications. For mobile phones, however, because of their centrality in public concerns, all studies are reviewed in detail.

23 The principal conclusions of the Advisory Group are given in Chapter 8 and recommendations for further research are given in Chapter 9.

24 The report concludes with a number of appendices. An overview of instrumentation that can be used for measuring exposures to electric and magnetic fields is given in Appendix A. Exposure guidelines for electromagnetic fields recommended by ICNIRP are summarised in Appendix B, with examples of how exposure measurements relate to the appropriate guidelines. Finally Appendix C summarises current research in the UK on health effects of RF exposure from mobile phones and base stations.

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2 Electromagnetic Fields, Sources and Exposure

1 Radiofrequency (RF) fields are generated either deliberately as part of the global telecommunications networks or adventitiously as part of industrial and other processes utilising RF energy. People both at home and at work are exposed to electric and magnetic fields arising from a wide range of sources that use RF electrical energy.

2 The RF electric and magnetic fields vary rapidly with time. The rates at which they vary cover a wide spectrum of frequencies and lie within that part of the electromagnetic spectrum bounded by static fields and infrared radiation. In this document the frequencies considered lie between 3 kHz and 300 GHz. This range includes a variety of RF sources in addition to those used for telecommunications. These are shown in Figure 2.1, together with the International Telecommunications Union (ITU) bands.

3 Even at the highest frequency of the range, 300 GHz, the energy quantum, $h f$, where h is Planck's constant and f is frequency, is still around three orders of magnitude too small to cause ionisation in matter. This region of the spectrum, together with optical frequencies, is therefore referred to as non-ionising.

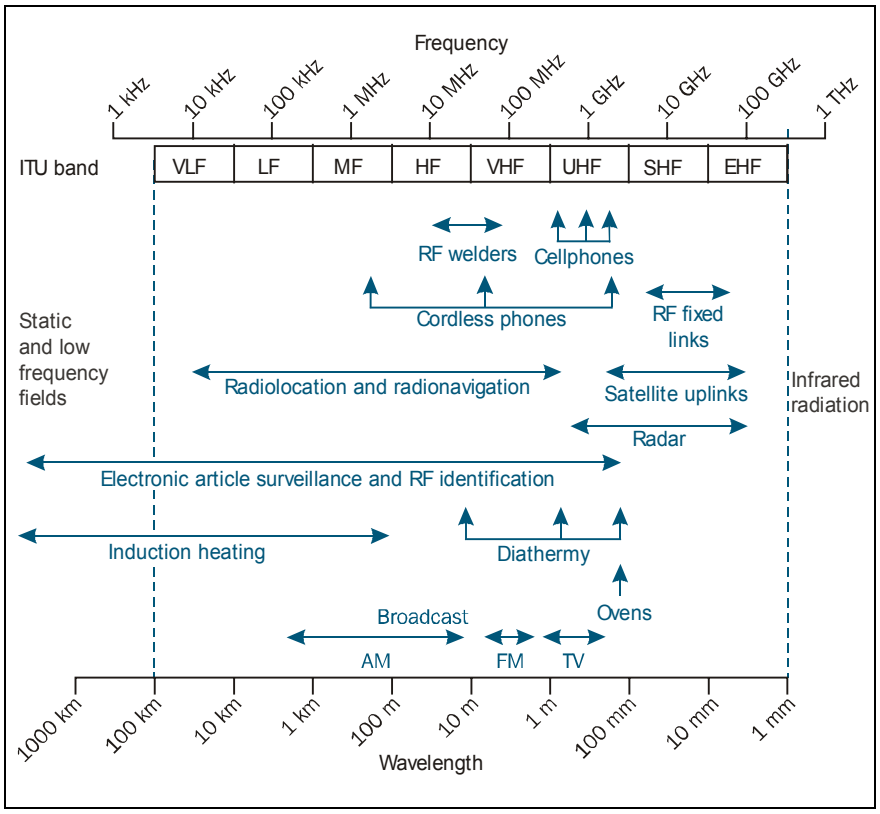


FIGURE 2.1
RF spectrum and sources

TABLE 2.1 *Sources of RF radiation across the spectrum and typical field strengths/power densities at accessible locations*

Frequency band	Description	Source	Frequency	Typical exposure*	Remarks
3 kHz	VLF Very low frequency	Induction heating	Up to 25 kHz	12 – 1000 A m^{-1}	Occupational exposures at close approach to coils, 0.1–1 m
		TV/VDU	15 – 30 kHz	1 – 10 V m^{-1}, 0.16 A m^{-1}	Public sitting at 30 cm from VDU
30 kHz	LF Low frequency	Induction heating	100 kHz	800 A m^{-1}	Limb exposures at close approach (0.1 m) to coils
		Electronic article surveillance (EAS)	130 kHz	Up to 20 A m^{-1}	Public exposure midway between panels when entering or leaving premises
300 kHz	MF Medium frequency	AM radio	415 kHz – 1.6 MHz	450 V m^{-1}	Occupational exposure at 50 m from AM broadcast mast
		Induction heating	300 kHz – 1 MHz	0.2 – 12 A m^{-1}	Occupational exposure
3 MHz	HF High frequency	Short-wave broadcast	3.95 – 26.1 MHz	340 V m^{-1}	Occupational exposure beneath wire feeders of 750 kW transmitter
		EAS	8 MHz	0.2 A m^{-1}	Public exposure close to a tag deactivating system
		PVC welding	27.12 MHz	Body: 100 V m^{-1}, 5 A m^{-1} Hands: 1500 V m^{-1}, 7 A m^{-1}	Operator position close to welding platform of a 10 kW dielectric heater
		Wood gluing	27.12 MHz	170 V m^{-1}	Operator body exposure at 50 cm from a 2 kW wood gluing machine
		CB radio	27 MHz (< 10 W)	1 kV m^{-1}, 0.2 A m^{-1}	Public exposure close to antenna of radio
30 MHz	VHF Very high frequency	FM radio	88 – 108 MHz	4 V m^{-1}	Public exposure at 1500 m from a 300 kW FM mast

Frequency band	Description	Source	Frequency	Typical exposure*	Remarks
300 MHz	UHF Ultra high frequency	TV, analogue	470 – 854 MHz	3 V m^{-1}	Public exposure (maximum at ground level) from a high power 1 MW effective radiated power TV transmitter mast
		GSM handsets	900 MHz 1800 MHz	400 V m^{-1}, 0.8 A m^{-1} 200 V m^{-1}, 0.8 A m^{-1}	At 2.2 cm from a 2 W phone At 2.2 cm from a 1 W phone
		GSM base station	900 and 1800 MHz	1 mW m^{-2} (0.6 V m^{-1}, 1.6 mA m^{-1})	Public exposure at 50 m from a mast operating at a maximum of 50 W per channel
		Very Small Aperture Terminal (VSAT) Satellite Earth Station	1.5/1.6 GHz	8 W m^{-2}	Main beam direction
		Microwave cooking	2.45 GHz	0.5 W m^{-2}	Public exposure at 50 cm from an oven leaking at BSI emission limit
3 GHz	SHF Super high frequency	Radar air traffic control	1 – 10 GHz 2.8 GHz	0.5–10 W m^{-2} 0.16 W m^{-2}	Exposure at 100 m from ATC radars operating over a range of frequencies
		VSAT	4 – 6 GHz	< 10 W m^{-2}	Maximum in the main beam
		Satellite news gathering	11–14 GHz	< 10 W m^{-2}	Maximum in the main beam
		Traffic radar	9 – 35 GHz	< 2.5 W m^{-2} < 1 W m^{-2}	Public exposure at distances of 3 m and 10 m from 100 mW speed check radar
30 GHz – 300 GHz	EHF Extra high frequency	Transmission digital and analogue video signals	38 GHz/55 GHz	< 10^{-4} W m^{-2}	Public exposure at 100 m outside main beam of microwave dish

* These are typical exposures at high frequencies and in the far field of sources where the electric and magnetic field strengths are orthogonal to each other and to the direction of propagation and there is a simple relationship between *E* and *H* that means the wave can be described in terms of its power density. Measurement of either *E* or *H* is sufficient to determine the power density. At lower frequencies and in the near field no such simple relationship exists. Sources that operate at relatively high current and low voltage, eg induction heaters tend to be defined by the measurement of magnetic field. At frequencies above 30 MHz fields tend to be determined using electric field strength measurements. In situations where people couple closely to the transmitter, such as in the use of mobile phones, the external field strengths are not an appropriate indicator of exposure and comparison with exposure guidelines requires an assessment of the relevant internal dosimetric quantity.

4 In contrast to ionising and ultraviolet radiation, where natural sources contribute the greater proportion of the exposure to the population, man-made sources tend to dominate exposure to time-varying electromagnetic fields over the spectrum shown in Figure 2.1. Over parts of the frequency spectrum, such as those used for electrical power and broadcasting, man-made fields are many thousands of times greater than natural fields arising from either the sun or the Earth. In recent decades the use of electrical energy has increased substantially, both for power distribution and for telecommunications purposes, and it is clear that exposure of the population in general has increased.

5 The potential for people to be exposed depends not only on the strength of the electromagnetic fields generated but also on their distance from the source and, in the case of directional antennas such as those used in radar and satellite communications systems, proximity to the main beam. High power broadcast and highly directional radar systems do not necessarily present a source of material exposure except to specialist maintenance workers or engineers. Millions of people, however, approach to within a few centimetres of low power RF transmitters such as those used in mobile phones and in security and access control systems where fields can give rise to non-uniform, partial-body exposure. The field strengths often decrease rapidly with distance from a particular source.

6 Everyone is exposed continually to low level RF fields from transmitters used for broadcast television and radio, and for mobile communications. Many individuals will also be exposed to low level fields from microwave communications links, radar, and from domestic products, such as microwave ovens, televisions and VDUs. Higher exposures can arise for short periods when people are very close to sources such as mobile phone handsets, portable radio antennas and RF security equipment.

7 Some of the sources of electromagnetic fields and the levels to which people are exposed both at work and elsewhere are shown in Table 2.1. The signals generated by various sources across the spectrum may be very different in character. While the underlying waveform from a source is usually sinusoidal, the signal may then, for example, be amplitude modulated (AM) or frequency modulated (FM) for radio communication or pulse modulated for radar (Figure 2.2). Modern digital radio communication systems can use more than one of these types of modulation in the same signal (Figure 2.3).

8 Many industrial sources produce waveforms with high harmonic content resulting in complex waveforms (Figure 2.4).

9 Electric and magnetic field strengths outside the body are commonly used to describe exposure to the fields generated by RF sources. However, any biological effects would be the result of exposure within the body, although this cannot usually be measured directly. The nature of the fields and characteristics of particular RF sources differ considerably and the waveform, spatial and temporal characteristics of the field are important in exposure assessment and their effect on instrumentation.

10 This chapter is concerned with exposure and its assessment arising from a wide variety of sources of RF fields. It gives general background information about the nature of electromagnetic fields and their interactions with the body before considering specific sources and summarising the exposures they create. Appendices A and B should be read in conjunction with this chapter. Appendix A illustrates and describes the types of equipment used for measuring fields, while Appendix B summarises the

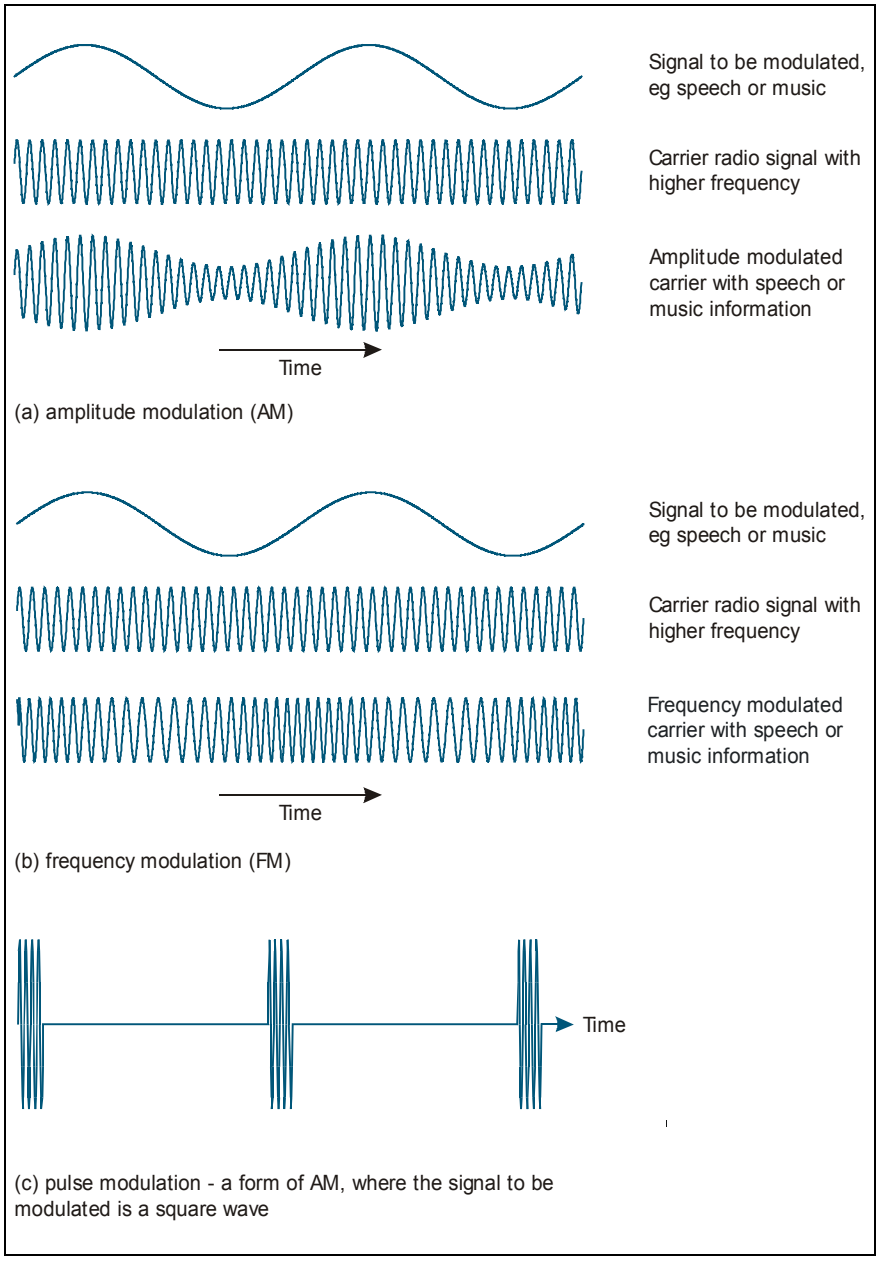


FIGURE 2.2
Different forms of analogue modulation commonly applied to radio signals

restrictions on exposure advised in international guidelines by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and sets a context to field measurements from sources by comparing them with the guideline levels. Further details of some of the issues relating to mobile phones and TETRA handsets and their base stations are given in earlier reports (IEGMP, 2000; AGNIR, 2001).

FIGURE 2.3
Examples of two simple digital modulation schemes

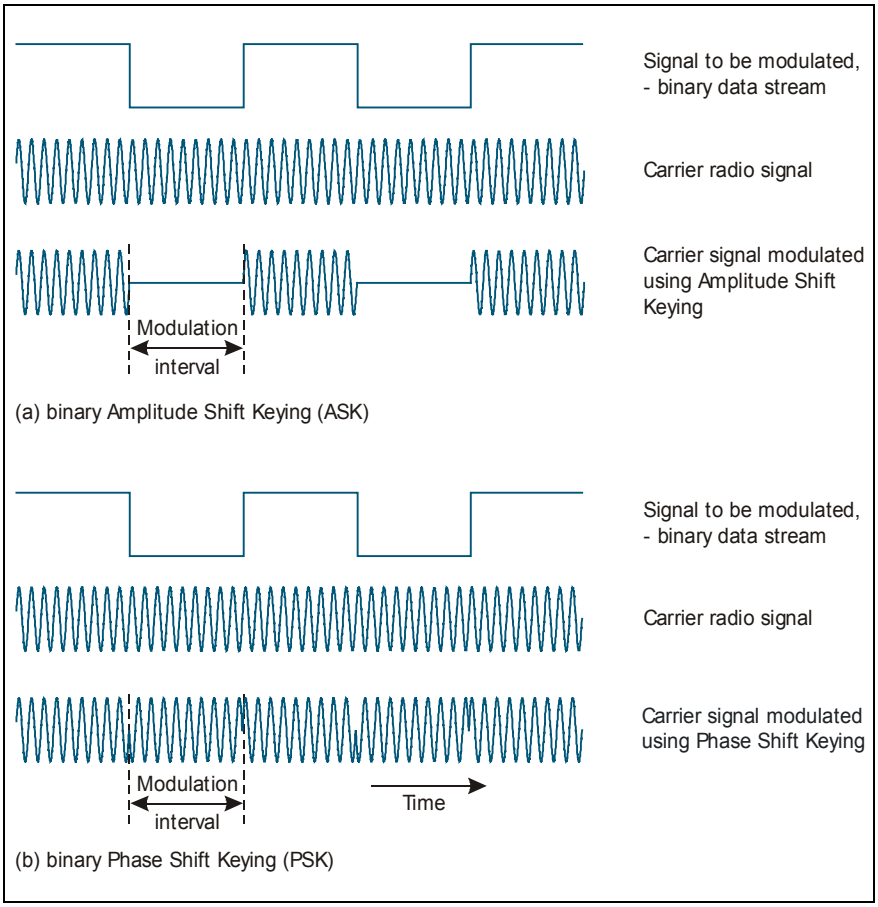
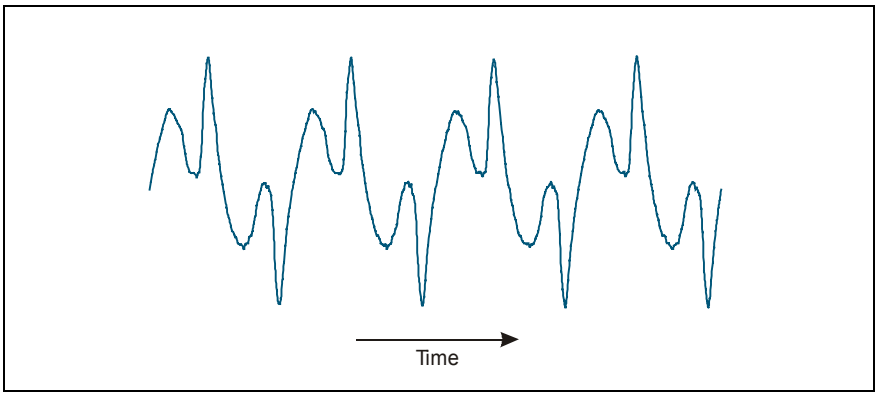


FIGURE 2.4
Industrial magnetic field waveform with high harmonic content



CHARACTERISTICS OF ELECTROMAGNETIC FIELDS AND ASPECTS OF DOSIMETRY

11 The exposure to the body from an RF field is determined by the strength of the electric and magnetic fields inside the body, which are different to those outside. It is not usually possible, however, to measure these internal fields directly. So studies to evaluate exposure are normally carried out either by using computational methods or by making measurements on a physical model of the head or body. The computational methods rely upon the detailed anatomical information that can be obtained by magnetic resonance imaging plus information on the electrical properties of the different components of the body tissue, bone, etc. The physical models, or phantoms, that have been used range from hollow shells filled with a fluid whose electrical properties are similar to the average values of body tissue, to more complex models using materials of different electrical properties. The electric field at various points inside simple phantoms is often measured using a robotically positioned probe controlled by computer. This is the type of approach used in assessing energy deposition in phantom heads arising from mobile phones. At the lower frequencies, below around 100 MHz, it has also been possible to make direct measurements of the induced RF current flowing through the body and to earth. One technique uses a solenoidal coil placed around the ankles, or other parts of the anatomy; the RF body current passing through the coil induces a voltage in its windings.

12 For simple exposure conditions the strength of the electromagnetic fields inside the body, and hence exposure, can also be assessed to a reasonable approximation from the strength of the fields present in that region before the body is placed there.

General characteristics of electromagnetic fields

13 An electromagnetic field or wave consists of electric, E, and magnetic, H, fields that oscillate sinusoidally between positive and negative values at a frequency, f. The distance along a wave between two adjacent positive (or negative) peaks is called the wavelength, λ, and is inversely proportional to the frequency. The strength of the electric or magnetic field can be indicated by its peak value (either positive or negative), although it is more usually denoted by the rms, or root mean square, value (the square root of the average of the square of the field). For a sinusoidally varying field, this is equal to the peak value divided by 1.4 ($\sqrt{2}$). At a sufficient distance from the source where the wave can be described as a plane wave, the electric and magnetic fields are at right angles to each other and also to the direction in which the energy is propagating. The amount of electromagnetic energy passing through a point per unit area at right angles to the direction of flow and per second is called the power density (intensity), S. So, if a power of 1 W passes through one square metre, the power density is 1 W m^{-2}.

14 A long way from a transmitter, the positive (or negative) peaks in the electric and magnetic fields occur at the same points in space. Hence, they are in phase, and the power density equals the electric field strength multiplied by the magnetic field strength, $S = E.H$.

Modulation

15 Where information such as speech is to be conveyed by radio, it is first converted into an electrical signal. This signal, which is of much lower frequency than RF, is then mixed with an RF signal. This mixing process is called modulation and can be achieved

in a number of ways. For example, in amplitude modulation (AM) the amplitude of the RF signal follows the fluctuations of the low frequency signal (see Figure 2.2a), while in frequency modulation (FM) the frequency changes by small amounts proportional to the size of the low frequency signal at that time (see Figure 2.2b). The RF signal that carries the information is called the carrier wave. Digital modulation systems involve defining a number of fixed amplitude and phase states for a carrier wave and then modulating the carrier wave so that it changes from one state to another according to the data to be transmitted (see Figure 2.3).

16 Complex waveforms are not confined to signals generated by communication systems. For example, in the case of cathode ray tube displays such as those used in televisions and VDUs, the electron beam has to travel rapidly across the width of the tube and back even faster. The deflection is produced by an electric field with a variation in time, which resembles a saw-tooth.

Pulsing (pulsed modulation)

17 RF signals are often transmitted in a series of short bursts or pulses – for example, in radar applications. Radar pulses last for a time that is very short compared with the time between pulses. The pulse duration could be one microsecond (one-millionth of a second), while the time interval between pulses could be one millisecond (one-thousandth of a second). The signal reflected from a distant object also consists of a series of pulses and the distance of the object is determined by the time between a transmitted pulse and its reflection. The long interval between pulses is needed to ensure that an echo arrives before the next transmitted pulse is sent. Thus, a feature of radar signals is that the average RF power output over time is very much less than the power transmitted within a pulse, which is known as the peak power. The ratio of the time-averaged power to the peak power is known as the duty factor.

18 GSM mobile phone signals and TETRA handset signals (see paragraphs 37 and 43, respectively) are also pulsed, and in these cases pulsing is introduced to achieve time division multiple access (TDMA). This allows each frequency channel to be used by several other users who take it in turns to transmit (IEGMP, 2000; AGNIR, 2001). For GSM phones and base stations, a 0.58 ms pulse is transmitted every 4.6 ms resulting in pulse modulation at a frequency of 217 Hz; pulsing also occurs at 8.34 Hz and at certain other frequencies (IEGMP, 2000). The most recent GSM phones, often described as 2½G, have enhanced data capabilities and can transmit pulses of greater durations that are multiples of 0.58 ms. In the extreme case, pulses that fill the entire 4.6 ms could be produced and pulsing would disappear. For TETRA handsets and mobile terminals, the main pulse frequency is 17.6 Hz. The signals from TETRA base stations are continuous and not pulsed (AGNIR, 2001).

19 Third generation (3G) mobile phones use a system that in Europe is called UMTS (Universal Mobile Telecommunications System). The modulation system, code division multiple access (CDMA), allows several users to use the same frequency channel by 'labelling' each of their transmissions with a specific coding scheme. The UMTS standards allow for communications to be carried out between handsets and base stations using either frequency division duplex (FDD) mode or time division duplex (TDD) mode. FDD mode is used with systems currently being deployed in the UK and this uses separate frequency channels for transmissions from the handset and the base station. Each transmission is continuous and so there is no pulsing, although the adaptive power control

updates (see paragraph 41) that occur at a rate of 1500 Hz will cause this component to 'colour' the otherwise broad spectrum of the power modulation. With TDD mode, transmissions are produced in bursts at the rate of 100 Hz and so pulsing would occur at this frequency, in addition to the frequency of the adaptive power control.

Source-dependent considerations

20 The properties of an electromagnetic field change with distance from the source. They are simplest at distances more than a few wavelengths from the source and a brief description of properties in this far-field region is given below. In general, the fields can be divided into two components: radiative and reactive. The radiative component is that part of the field which propagates energy away from the source, while the reactive component can be thought of as relating to energy stored in the region around the source. The reactive component dominates close to the source in the reactive near-field region, while the radiative part dominates a long way from it in the far-field region. Whilst the reactive field components do not contribute to the radiation of energy, the energy they store can be absorbed and indeed they provide a major contribution to the exposure of people in the near-field region. The measurement of the reactive components of the field can be particularly difficult since the introduction of a probe can substantially alter the field.

21 Roughly speaking, distances within about one-sixth of a wavelength ($\lambda/2\pi$) from the source define the reactive near-field region, while distances greater than $2D^2/\lambda$ (where D is the largest dimension of the antenna) define the far-field region. Since D is usually comparable in size to λ (or larger), $2D^2/\lambda$ is roughly comparable to λ (or greater). Distances between $\lambda/2\pi$ and $2D^2/\lambda$ form a transition region in which radiative field components dominate, but the angular distribution of radiation about the source changes with distance. This is known as the radiating near-field region. Since wavelength is inversely proportional to frequency, it varies considerably, from 1 mm to 100 km over the range of RF frequencies considered here (3 kHz – 300 GHz). Hence, for frequencies above 300 MHz (or 1 m wavelength) exposure tends to occur in the far-field region except when approaching very close to the source. This is not the case at lower frequencies.

Far-field characteristics

22 As already noted, the power density of an electromagnetic wave, S, is equal to the product of the electric and magnetic fields, $S = EH$. Since $E = 377H$ (assuming the quantities are all expressed in SI units), this becomes

$$S = E^2/377 = 377H^2 \quad (\mathrm{W\,m^{-2}})$$

Hence $E = 19\sqrt{S}$ $(\mathrm{V\,m^{-1}})$ and $H = 0.052\sqrt{S}$ $(\mathrm{A\,m^{-1}})$

23 Table 2.2 illustrates the far-field values of electric field strength and magnetic field strength for power densities from 0.1 to 100 $\mathrm{W\,m^{-2}}$.

Near-field characteristics

24 The field structure in the reactive near-field region is more complex than that described above for the far-field. Generally, the electric and magnetic fields are not at right angles to each other and they do not reach their largest values at the same points in space, ie they are out of phase. Hence, the simple relation between S, E and H given in Table 2.2 is not obeyed and calculations of energy absorption in tissue in this region are more complicated than in the far-field region.

TABLE 2.2
Examples of far-field (plane-wave) relationships

Power density ($W\ m^{-2}$)	Electric field strength ($V\ m^{-1}$)	Magnetic field strength ($A\ m^{-1}$)
0.1	6.1	0.016
1.0	20	0.052
10	61	0.16
50	140	0.36
100	200	0.51

Dosimetry

25 Dosimetry is the term used to describe the process of determining internal quantities relating to exposure in tissues such as the electric field strength, induced current density and energy absorption rate, from external fields. Both experimental and numerical dosimetry techniques are used. The experimental techniques frequently involve the use of fluids with electrical properties similar to the averages for those of the exposed tissues. Very small probes are used to measure the electric fields inside the models, while minimising the changes in the fields produced by the presence of the probe. The numerical techniques use anatomically realistic models of an average person, together with values of the electrical properties for the different simulated tissues in the model. Both dosimetric techniques can calculate internal fields for a fixed body and source geometry – for example, that which might be expected to give maximum coupling between them, and hence maximum exposure. Neither numerical nor physical phantoms can easily be flexed at joints, so considering moving people requires a number of fixed positions to be evaluated in sequence. Given the effort involved with constructing multiple phantoms and performing multiple assessments, this poses a challenge for evaluating typical time-averaged exposures in terms of dosimetric quantities.

26 At frequencies below 100 kHz, the electrical quantity identifiable with most biological effects is the electric field strength in tissue, which is related to the current density. However, the more appropriate quantity at higher frequencies is the specific (energy) absorption rate, SAR, which is related to the electric field strength squared in tissue. At frequencies above about 1 MHz, the orientation of the body with respect to the incident field becomes increasingly important. The body then behaves as an antenna, absorbing energy in a resonant manner that depends upon the length of the body in relation to the wavelength. For standing adults, the peak of this resonant absorption occurs in the frequency range 70–80 MHz if they are electrically isolated from ground, and at about half this frequency if they are electrically grounded. Smaller people and children show the resonance characteristic at higher frequencies. In the body resonance region, exposures of practical significance arise in the reactive near-field where coupling of the incident field with the body is difficult to establish owing to non-uniformity of the field and changing alignment between the field and body. In addition, localised increases in current density and SAR may arise in parts of the body as a consequence of the restricted geometrical cross-section of the more conductive tissues.

27 As the frequency increases above the resonance region, power absorption becomes increasingly confined to the surface layers of the body and is essentially confined to the skin above a few tens of GHz.

Body currents

28 Body currents in people can be determined using a whole-body model. Currents induced by electric fields usually flow through the legs and feet to the floor (ground). So the currents can be obtained from the voltage drop across a resistance placed between the feet and the floor or by using a coil around the ankles. The situation is more complicated, however, if the currents are eddy currents induced by magnetic fields. Such currents circulate about the cross-section of the body, are greatest near the surface and do not usually leave the body through the feet or at any other point. Hence they are difficult to measure.

Specific (energy) absorption rate (SAR)

29 The rate at which energy is absorbed by a particular mass of tissue, m, is $m\sigma E^2/\rho$, where σ and ρ are, respectively, the electrical conductivity and density of the tissue and E is the rms value of the electric field strength. The quantity $\sigma E^2/\rho$ is called the specific (energy) absorption rate and is measured in watts per kilogram ($W\,kg^{-1}$). It varies from point to point in the body both because the electric field changes with position and also because the conductivity is different for different types of tissue (the density is much the same for all tissues apart from bone). In practice, the SAR may be ascertained by averaging over a small mass of tissue or over the whole body mass. Both approaches are used for comparison with the limits on exposure advised in protection guidelines.

30 The most commonly used methods for the direct experimental measurement of SAR involve measurement of the internal electric field strength or the rate of temperature rise within an exposed object. The internal electric field strength may be measured with an implantable *E*-field probe but this is not practicable where living people are concerned. So, as noted earlier (see paragraph 11), SARs are usually measured using phantoms or are calculated.

RADIOFREQUENCY SOURCES AND EXPOSURE

31 The sources of exposure discussed in this section include intentional radiators such as the antennas used for telecommunications, RF identification, and security and access control. Other sources include those that give rise to adventitious emission of RF fields – for example, those used for induction heating, dielectric heating and in microwave cooking. Many of the measurements reported here are 'spot measurements', ie they are made at a point in space and at a point in time. Often the data represent maximum field strengths that a person may encounter when near a source, as is appropriate for comparison with reference levels (ICNIRP, 1998). Sometimes the spot measurements are analysed further to take account of time and spatial variations in the electromagnetic field, particularly where spot measurements show the presence of field strengths approaching the ICNIRP reference levels.

Communications

32 Antennas generate electromagnetic fields across the spectrum. At very low frequencies (VLF) the structures are massive with support towers 200–250 m high and the fields may be extensive over the site area. Electric field strengths of several

hundred V m^{-1} may be encountered within the boundary defined by the antenna structures. Magnetic field strengths in the range 2–15 A m^{-1} have been measured close to VLF antenna feeds and 0.2–52 A m^{-1} close to LF towers. In transmitter buildings magnetic field strengths were in the range < 0.1 mA m^{-1} –11 A m^{-1}.

33 Through these frequency bands and up to about 100 MHz under uniform field exposure conditions, measurements and calculations have been made of induced currents related to external field strengths. The currents induced in the body that flow to ground through the feet (short-circuit current) rise to a theoretical maximum of 10–12 mA per V m^{-1} at the resonance frequency of around 35 MHz for an electrically grounded adult (Chen and Gandhi, 1989; Dimbylow, 1991). Measurements indicate that under more normal grounding conditions, eg when wearing shoes, the current is reduced to about 6–8 mA per V m^{-1}.

34 At distances from antennas comparable to or smaller than their physical dimensions, field distributions can be non-uniform. This is particularly so for mobile and portable systems where the field strengths change rapidly with distance from the antenna. Electric field strengths of about 1300 V m^{-1} have been measured at 5 cm from 4 W CB transmitters, whereas at 60 cm the field strengths fall to less than 60 V m^{-1} (Lambdin, 1978).

35 In the USA, long before the advent of mobile telephony a study of population exposure to background fields from VHF and UHF broadcast transmitters (Tell and Mantiply, 1980) showed that the median exposure for 15 cities was 50 μW m^{-2} (0.14 V m^{-1}), although some cities had median exposures of 200 μW m^{-2} (0.3 V m^{-1}). Maximum exposures, which were from local FM radio stations, were about 0.1 W m^{-2} (6 V m^{-1}). These values are all well within the ICNIRP reference levels of about 25 to 60 V m^{-1} for this frequency range (ICNIRP, 1998).

Handheld equipment

36 Handheld radio transmitters include mobile phones, cordless phones, emergency service communications (eg TETRA) and professional mobile radios PMRs (walkie-talkies). Newer devices include laptop, palmtop and wearable computers with built-in antennas. The radiating structures of these devices tend to be integrated into or onto their body-shell and will typically be within a few cm of the user's body. The output power levels range from a few mW for cordless phones up to a few watts for PMRs, and the frequency bands range from 30 MHz to 5 GHz.

Mobile phones

37 The most widespread handheld transmitter is the mobile phone. The large majority of mobile phones in use in the UK are so-called second generation or 2G phones and use the GSM900 or GSM1800 systems. Table 2.3 lists these systems and also some other systems that are available in the world. Rather few analogue (first generation) phones are still in use and the UK networks, which used ETACS (an extension to the Total Access Communications System), were shut down in 2000/2001. First generation networks used in other parts of the world include AMPS (Advanced Mobile Phone Systems) and NMT (Nordic Mobile Telephony). Second generation networks in North America include D-AMPS, CDMA IS-95 and PCS, or GSM1900. PDC phones are used in Japan.

Mobile phone system	Type	Frequency band (MHz)	Maximum time-averaged power (W)
NMT (Nordic Mobile Telephone)	Analogue	450, 900	1
ETACS (Extended Total Access Communications System)	Analogue	900	0.6
AMPS (Advanced Mobile Phone System)	Analogue	800	0.6
D-AMPS (Digital AMPS)	Digital	800, 1900	0.2
GSM900 (Global System for Mobile Telecommunication)	Digital	900	0.25
GSM1800/1900	Digital	1800, 1900	0.125
IS-95 (CDMA Code Division Multiple Access)	Digital	800, 1900	0.2
PDC (Personal Digital Cellular)	Digital	800/1500	0.2

TABLE 2.3 *Mobile phone systems and handset powers*

38 The table does not include the 2½G phones (GPRS, HSCSD, EDGE) currently being introduced as extensions to GSM to allow access to the internet etc, or the 3G phones (UMTS – Universal Mobile Telecommunications System) being introduced. The 2½G phones are extensions to GSM900/1800 with a maximum peak power output of 1 W. However, the average power output for data transmission can be higher than with voice transmissions since there may be transmission for more than one-eighth of the time. Even so, when using the phone for data transmission it would not normally be held close to the head. Third generation phones in the UK operate around 1950 MHz and have the same output power as GSM phones operating in the 1800 MHz band, ie 125 mW.

39 At distances less than 1 cm from the antenna the localised electric field strengths may be hundreds of volts per metre. However, such localised field strengths produced in the absence of a body and so close to an antenna cannot be used as a ready measure of exposure. In these circumstances, the mutual interaction of the head and phone must be fully taken into account. The approach taken to determine exposure in people has been to use models and assess the internal dosimetric quantity, SAR, as a function of the power fed to the antenna (Dimbylow and Mann, 1994). Standardised procedures for assessing SAR have been developed by various bodies including CENELEC (2001) and manufacturers now provide information on measurements made on various models.

40 Figure 2.5 is an example of the maximum SAR values measured in a phantom model of the head for a range of mobile phones. The values are maxima found when each of the phones was placed in a set of standard positions and radiated at a number of standard frequencies.

41 Whilst the SAR values are based on the maximum output power of the particular phone, the exposure of the user will vary according to location, the position of the phone relative to the head and the size of the head. The geographical location is particularly important since adaptive power control (APC) can reduce the power emitted by the phone by up to a factor of 1000. Personal exposure will also depend on the average number and duration of calls. Where compliance with guidelines is concerned, it is necessary to average over an appropriate time period specified, eg any six-minute period.

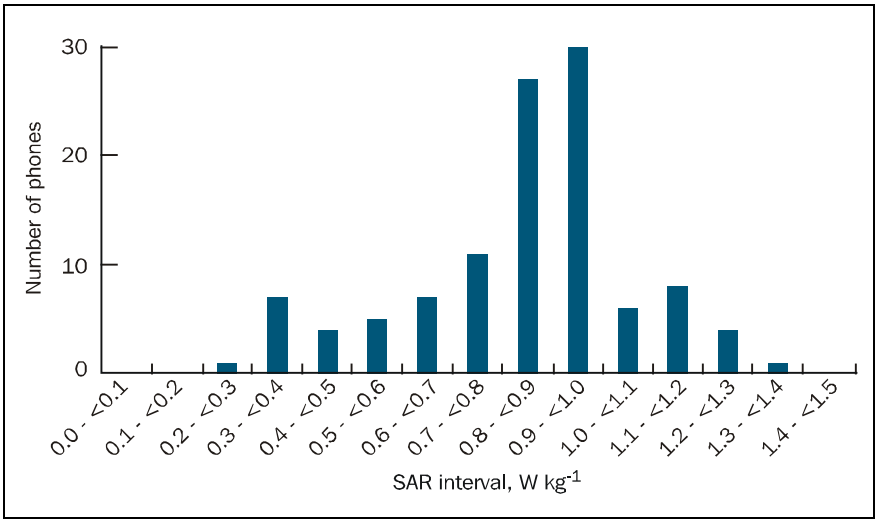


FIGURE 2.5
Distribution of SARs produced by 111 mobile phone handsets, as indicated by their manufacturers in June 2003

Cordless phones

42 Both analogue cordless phones (for example, CT0, CT1 and JCT) and digital cordless phones (for example, CT2, DECT and PHS) have average output power levels of around 10 mW. However, digital systems can involve time sharing and so peak powers can be higher – for example, with DECT the peak power is 250 mW with no adaptive power control and the emissions are in the form of 400 μs bursts. Average powers are thus ten or more times smaller than those from mobile phones operating at their highest power level (see Table 2.3). Hence, the powers should result in much smaller values of SAR than those shown in Figure 2.5. Even so, it is conceivable that in normal use phones favourably located with respect to a base station would reduce their output power and therefore the SAR below that of cordless phones.

TETRA

43 Since 1997, countries including the UK have been introducing an emergency service radio system known as terrestrial trunked radio (TETRA). The system operates using frequencies around 400 MHz and the digitally based features provide improved data transmission capabilities and added security over existing analogue systems. The features of the system, in particular the discontinuous nature of the waveform, which is similar to GSM in that TDMA (see paragraph 18) is used, and similar to older mobile radio in that it uses push-to-talk mode, have been considered in depth in an earlier report by the Advisory Group (AGNIR, 2001). The duty factors of the hand-portable equipment mean that average powers for the 1 and 3 W transmitters are 0.25 and 0.75 W, respectively, but could increase if additional available channel space were to be utilised for data transmission. A comparison of output powers is given in Table 2.4.

44 Exposures have been estimated for maximum power transmission using experimental modelling (Gabriel, 2000) and the SAR produced in a phantom head is shown in Table 2.5. Increases due to channel utilisation would in theory increase the SAR by a factor of four but in practice the exposure conditions are likely to change when data rather than speech are being transmitted.

System	Maximum output power (W)		APC available
	Peak	Average	
Analogue police radio (450–460 MHz)	1.5	1.5	–
TETRA* Class 3 radio (380–385, 410–415 MHz)	3	0.75	✓
TETRA* Class 4 radio (380–385, 410–415 MHz)	1	0.25	✓
GSM900 (890–915 MHz)	2	0.25	✓
GSM1800 (1710–1785 MHz)	1	0.125	✓

* APC is available for TETRA handsets in their usual trunked mode of operation, but not when they are used in direct mode (AGNIR, 2001).

TABLE 2.4 *Peak and time-averaged output powers for various types of different handheld radio terminals when operating at their maximum power level (the average figures for TETRA are for one time-slot)*

	SAR (W kg^{-1}) for 1 W radio			SAR (W kg^{-1}) for 3 W radio		
	Spatial peak	1 g averaged	10 g averaged	Spatial peak	1 g averaged	10 g averaged
Left ear	1.40	1.16	0.89	5.07	3.92	2.88
Right ear	1.72	0.94	0.88	5.07	2.74	2.33
Front	0.35	0.28	0.24	0.92	0.72	0.53

TABLE 2.5 *Measured SARs produced in a phantom head exposed to radio signals from 1 and 3 W TETRA hand portables*

Bluetooth technology

45 This is a technique for connecting mobile devices (computer, mouse, mobile phone, etc) using radio rather than wires. The systems operate at 2.45 GHz with a 1 mW peak power permitting them to be used over a 10 m range. The low power outputs will give rise to correspondingly low exposures, well below guideline levels.

Wireless local area networks (wireless LANs)

46 These are systems for networking computers and other portable devices via radio. The computer terminals are known as clients and have antennas either mounted outside their body-shell or integrated internally. The clients communicate to fixed access points with antennas that receive/transmit the radio signals from/to the clients and provide an interface with a conventional wired computer network.

47 Many of these systems use the IEEE802.11a and IEEE802.11b standards (IEEE, 1999, 2000), which are limited to peak output powers of 100 mW in Europe. IEEE802.11a uses frequencies in the bands 5.15–5.25, 5.25–5.35 and 5.725–5.825 GHz, and a modulation scheme known as OFDM (orthogonal frequency division multiplexing). IEEE802.11b uses frequencies in the 2.4–2.4835 GHz range with spread-spectrum modulation, using either CDMA or frequency hopping. Wireless LAN transmissions are intermittent and so time-averaged powers will be lower and depend on the amount of data transmitted by a device.

48 Exposures to wireless LAN equipment will depend on how the transmitting antennas are located with respect to the body, the duration of any transmissions and the peak output power. NRPB has made measurements of the power density of radio waves generally in and about the offices where wireless LANs are deployed and these have always been found to be very much below the ICNIRP reference levels (ICNIRP, 1998). The situation is rather more complicated for exposure within the first few cm of the transmitters, eg for the situation where a laptop computer is placed on someone's lap. This is the situation where exposure would be highest and there is no practical

assessment that can be rapidly performed to check levels with an installed system. Nevertheless, given the low powers, it would be expected that these would comply with current guidelines.

Hands-free kits

49 An important feature of hands-free kits for use with mobile phones is that they move the major source of RF exposure, the antenna, away from the head and sometimes also from other parts of the body. The kits consist of an earpiece and a microphone connected to the phone either with wires or a wireless Bluetooth radio link. The use of a hands-free kit would be expected to reduce the SAR in the head because of the increased distance between the antenna and the head and because connecting wires would not be expected to form an efficient RF waveguide. Nevertheless, it has been claimed that, under certain conditions, the SAR near to the earpiece of a wired hands-free kit can exceed the SAR at the same point from the phone when that is held next to the head (Consumers' Association, 2000). However, the methodology used for this work has been criticised (Bit-Babik et al, 2003).

Fixed antennas – broadcast and telecommunications

50 The frequency bands used for broadcasting terrestrial radio and television services in the UK are shown in Table 2.6. The approximate number of transmitters, grouped by band and power, is shown in Table 2.7.

TABLE 2.6
Broadcasting bands in the UK

Designation	Frequency range	Usage
LF (long wave)	145.5 – 283.5 kHz	Radio
MF (medium wave)	526.5 – 1606.5 kHz	Radio
HF (short wave)	3.9 – 26.1 MHz	International radio
VHF (Band II)	87.5 – 108 MHz	FM radio
UHF (Band IV–V)	470 – 854 MHz	Television

TABLE 2.7
*Broadcast transmitters in the UK**

	Effective radiated power, ERP (kW)					
Service class†	0–0.1	> 0.1–1.0	> 1.0–10	> 10–100	> 100–500	> 500
Analogue TV	3496	589	282	122	86	19
Digital TV	134	177	192	2	–	–
DAB	4	126	121	–	–	–
VHF FM radio	632	294	232	98	72	–
MW/LW radio	14	125	38	19	12	–

* Compiled September 2003 from publicly available information.
† For TV sites, each analogue channel (eg BBC1) or each digital multiplex counts as one transmitter.

Digital terrestrial broadcasting

51 In the UK this comprises Digital Audio Broadcasting (DAB) radio services and Digital Video Broadcasting (DVB-T) for terrestrial (as opposed to satellite) television. Transmissions have also commenced in the MF and HF bands in the Digital Radio Mondiale (DRM) format. DAB in the UK uses frequencies in the 220 MHz region, a total of seven multiplexes have been allocated in the UK. The channel width of a DVB-T multiplex is 8 MHz (the same as a conventional TV channel), and the width of a DAB

multiplex is about 1.5 MHz. All systems are based on a digital modulation scheme – coded orthogonal frequency division multiplex (COFDM). In this scheme there are a number of discrete carrier frequencies spaced across the channel block which carry the digital information (DVB-T uses 1705, and DAB uses 1536, equally spaced carriers).

52 Modulation of the carriers implies that there are short-term excursions in output power, which in the extreme could lead to a maximum of 32 dB above the average output level. Engineering considerations mean that this is limited in practice to 10 dB (x 10) above the average value. The total power of the DAB and DVB-T transmissions is lower than that for analogue broadcasts; the highest power DVB-T transmitter has an average ERP (effective radiated power) of 10 kW per multiplex, as opposed to its analogue counterpart with a total of 1000 kW ERP per service. A DAB channel transmitter will also have an ERP up to 10 kW, but often lower. This can be compared with a main VHF FM transmitter ERP of 250 kW per service.

53 People subjected to the highest exposures will be antenna riggers and engineering staff working in transmitter halls or under open-wire antenna feed lines. The following sections present measurements that have been made in the vicinity of permanent broadcast installations.

MF and HF radio

54 Measurements have been made by NRPB of the electric and magnetic fields and body currents close to a number of HF broadcast antennas and feeder arrays where fields may be non-uniform and can vary by a factor of two over the body height.

55 In some localised areas, the maximum electric field was 340 V m^{-1}. Where the spatially-averaged value of the field strength over the body height was less than 60 V m^{-1}, induced body currents were below 100 mA. The maximum magnetic field strength was 0.5 A m^{-1} (Allen et al, 1994).

56 As part of a preliminary study to investigate if the exposure of broadcast and telecommunications workers can be appropriately categorised, personal dosemeters have been worn by various workers on HF sites to provide an indication of relative exposure. The exposure information so gathered was downloaded from data-logging devices attached to a commercially available 'pocket' instrument incorporating orthogonal electric and magnetic field sensors. Figure 2.6 shows a typical trace acquired in this way in which the electric field index of exposure is a percentage of the corresponding ICNIRP occupational reference level (ICNIRP, 1998).

57 Measurements at an MF station with one 50 kW and one 70 kW transmitter showed fields of 60 V m^{-1} beneath the antenna feeders. Fields in excess of 1500 V m^{-1} were measured 1.5 m from the half-wave vertical antenna mast.

58 In the USA measurements have been made of electric and magnetic field strengths at distances of 1 to 100 m from a number of AM broadcast towers (Mantiply et al, 1997) with operating powers from 1 to 50 kW over the frequency range from 500 kHz to 1.6 MHz. Within a metre or two of the towers electric field strengths were between 95 and 720 V m^{-1} and magnetic field strengths ranged from 0.1 to 9.3 A m^{-1}. At 100 m the electric and magnetic field strengths varied over an order of magnitude to 20 mV m^{-1} and 76 mA m^{-1}, respectively. A review of general population exposure (Hankin, 1986) revealed that the median exposure of the urban population to AM broadcast in the USA was 280 mV m^{-1} and 98% of the population were exposed to levels above 70 mV m^{-1}.

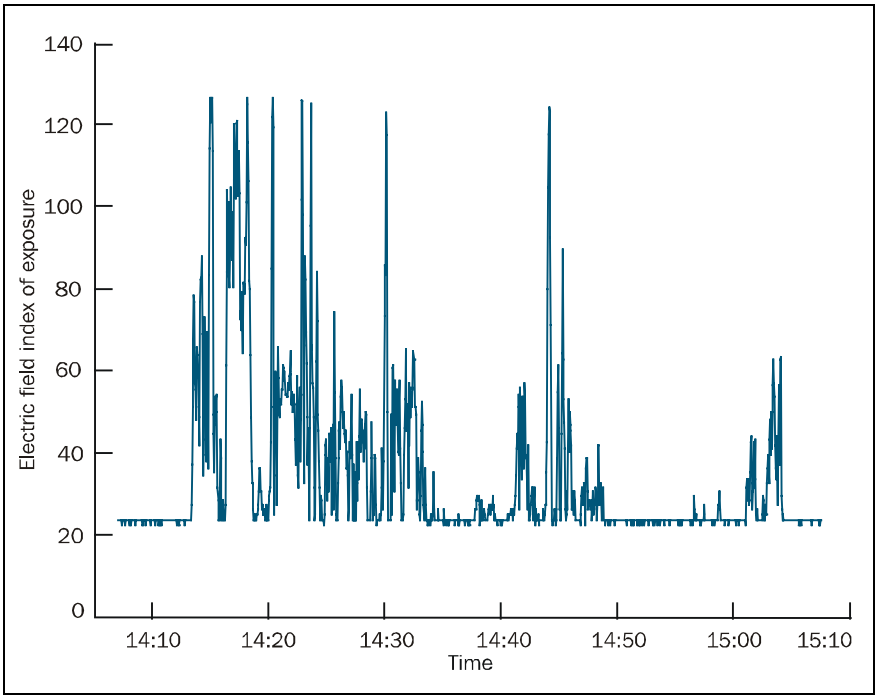


FIGURE 2.6 *Trace acquired from a body-mounted personal exposure meter worn by a worker at an HF broadcast site*

VHF transmitters

59 In a similar manner to that described for HF measurements, electric and magnetic field strengths have been assessed for antenna riggers while they were climbing on masts behind operating antenna stacks. Examples of the field variation during these periods are shown in Figures 2.7 and 2.8.

60 For one antenna rigger climbing through a 250 kW VHF FM antenna array, time- and spatially-averaged electric and magnetic field strengths were 92 V m^{-1} and 0.22 A m^{-1}, respectively; the peak fields encountered were 250 V m^{-1} and 0.38 A m^{-1}.

Mobile phone base stations

61 The mobile phone base station is ubiquitous and there are around 35 000 in the UK. Antennas used with *macrocellular* base stations are generally placed between 15 and 50 m above ground level because they are designed to provide communications over distances of several kilometres. *Microcellular* base stations have their antennas mounted nearer ground level as communications are only carried out over distances of a few hundred metres. *Picocellular* base stations provide localised coverage inside buildings. Antennas tend to be mounted directly on existing structures, such as buildings, when this is convenient, but ground-based lattice towers, shorter masts mounted on roofs, and lamp-post type systems are also used.

62 The power classes specified by standards for GSM transmitters operating at 900 and 1800 MHz are shown in Table 2.8. However, not all classes of transmitter are necessarily used in practice.

63 Base stations can utilise more than one transmitter but in the UK it is unlikely that a single transmitter operates at powers exceeding 100 W on a macrocellular site. Whilst

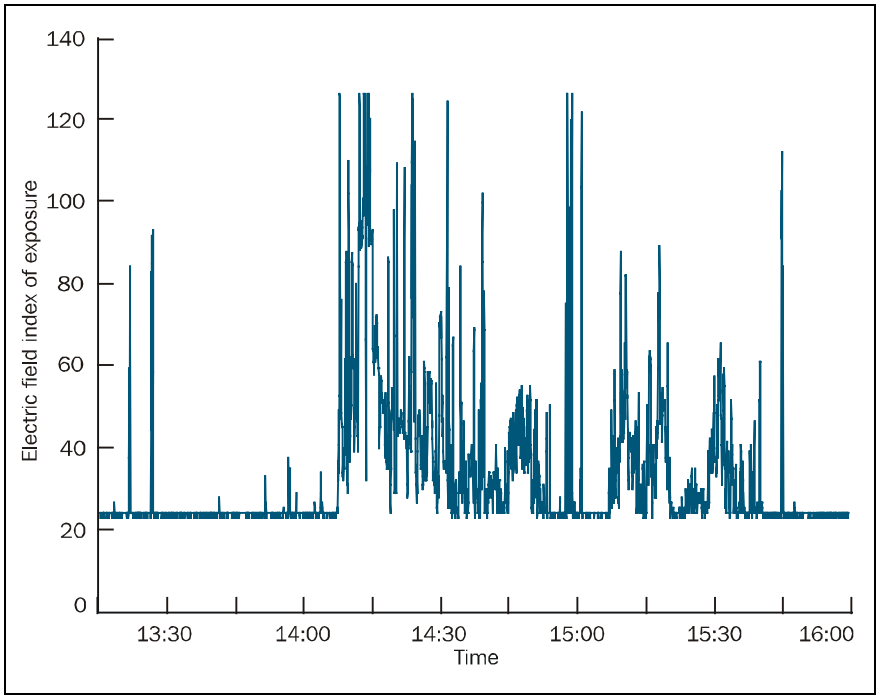


FIGURE 2.7 *Electric field trace acquired from a body-mounted personal exposure meter worn by a worker at a VHF broadcast site*

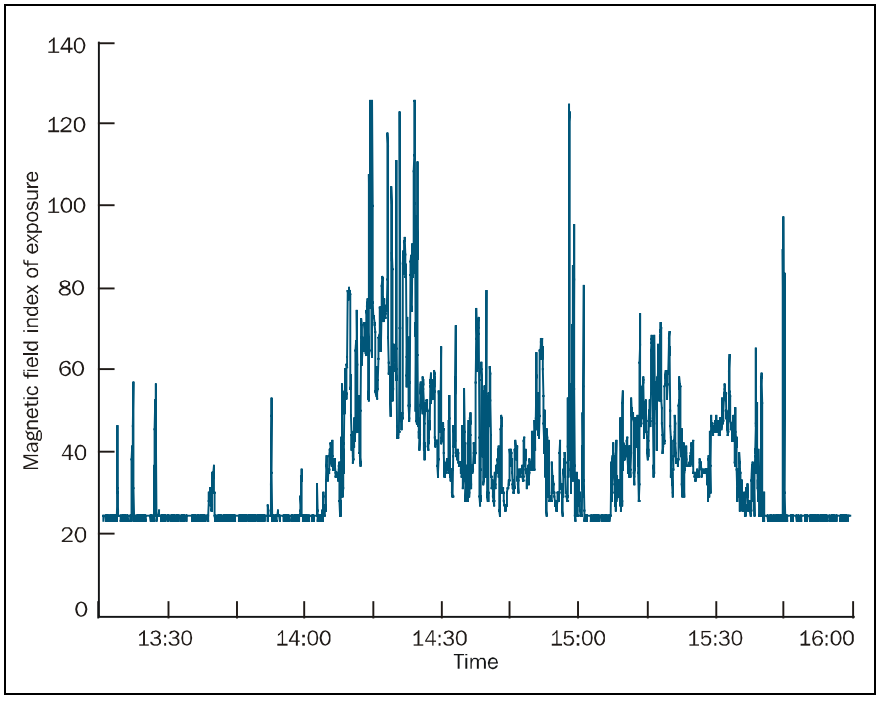


FIGURE 2.8 *Magnetic field trace acquired from a body-mounted personal exposure meter worn by a worker at a VHF broadcast site*

TABLE 2.8 *Output powers from GSM900 and GSM1800 base station transmitters, as defined in the GSM Phase 2+ technical standard*

GSM900			GSM1800		
Cell type	Power class	Power (W)	Cell type	Power class	Power (W)
Macro	1	320 – (<640)	Macro	1	20 – (<40)
	2	160 – (<320)		2	10 – (<20)
	3	80 – (<160)		3	5 – (<10)
	4	40 – (<80)		4	2.5 – (<5)
	5	20 – (<40)			
	6	10 – (<20)			
	7	5 – (<10)			
	8	2.5 – (<5)			
Micro	M1	(>0.08) – 0.25	Micro	M1	(>0.5) – 1.6
	M2	(>0.025) – 0.08		M2	(>0.16) – 0.5
	M3	(>0.008) – 0.025		M3	(>0.05) – 0.16
Pico	P1	(>0.02) – 0.1	Pico	P1	(>0.04) – 0.2

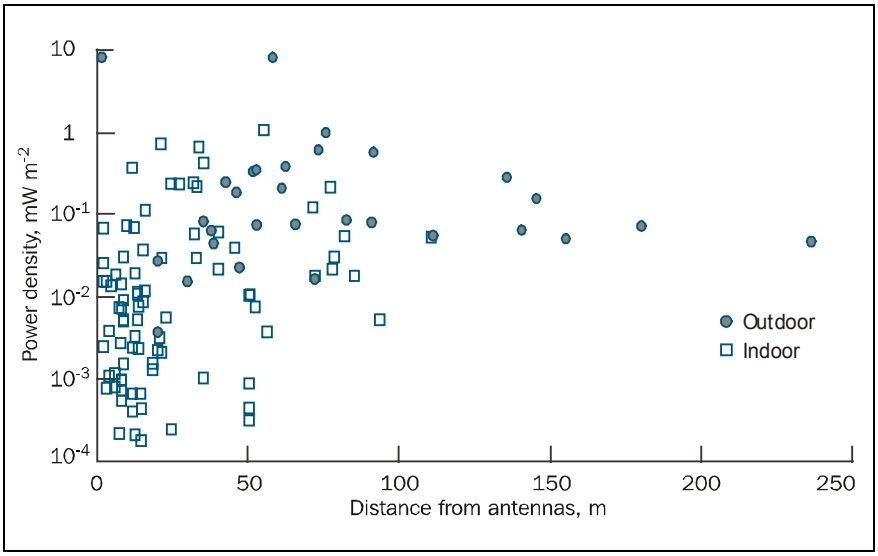
these are potential transmitter output powers, the power density arising from a particular antenna will depend upon power into the antenna and the gain of the antenna, the product of which gives the effective isotropic radiated power (EIRP). Licence restrictions placed on EIRP by the Radiocommunications Agency for purposes other than ensuring compliance with guidelines act to restrict the power density from individual transmitters.

64 In a study carried out by NRPB (Mann et al, 2000) at 118 locations on 17 sites, where signals were obtained from base stations, most of the exposures were between 10 $\mu W\ m^{-2}$ and 1 $mW\ m^{-2}$, the maximum being 8.3 $mW\ m^{-2}$. At locations where power density exceeded 1 $mW\ m^{-2}$, the local base stations dominated the signal strength and other environmental signals had little additional effect. Figure 2.9 shows the measured total power density from the base stations local to the measurement sites.

65 In 73 locations, all radio signals over the range from 30 MHz to 3 GHz were evaluated and these are summarised in Table 2.9 and Figure 2.10.

66 In the UK measurements have been carried out by the Radiocommunications Agency (2003) as part of a base station audit recommended by IEGMP (2000). The audit

FIGURE 2.9 *Total power density from local base stations*



	Geometric mean and range (5th–95th percentiles) of power density ($\mu W\ m^{-2}$)							
	Local base stations		Total of all signals		Total neglecting local base station		Total neglecting all base stations	
Indoor	17	(0.32–570)	75	(1.9–1000)	16	(0.76–970)	5.0	(0.23–420)
Outdoor	130	(19–930)	240	(49–1700)	37	(0.5–360)	12	(0.5–360)
All locations	33	(0.91–700)	110	(3.5–1100)	21	(0.84–970)	6.6	(0.23–380)

TABLE 2.9 *Geometric mean power densities*

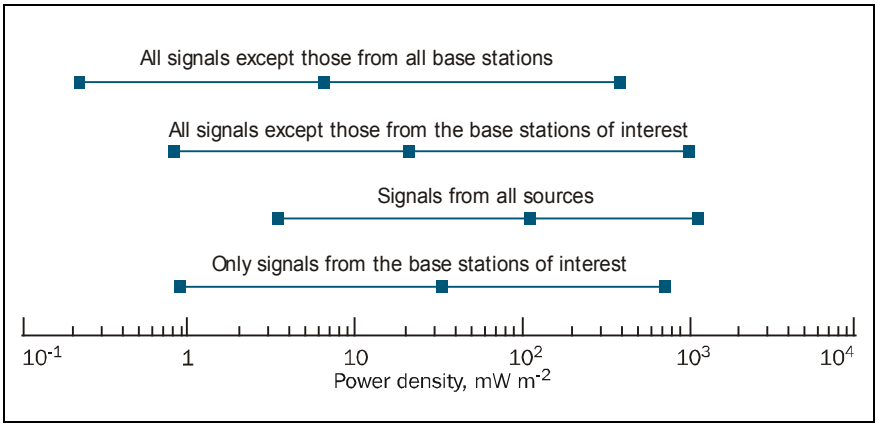


FIGURE 2.10 *Range and mean power density from all measured signals*

concentrated on what were described as 'sensitive sites' close to mobile phone base stations, such as schools and hospitals. In addition to the majority of GSM mobile phone signals, ten sites where TETRA antennas were mounted were assessed specifically with regard to the strength of those signals. The progress and results of the audit, including the TETRA measurements, are summarised in Table 2.10.

67 In all cases, measurements of fields from base stations at positions of normal public access show that exposures are a small fraction of exposure guidelines.

68 It has been suggested that, for epidemiological studies, an appropriate surrogate for exposure to base station fields might be the distance of a particular residence from the base station mast. There are material difficulties in using what appears to be a simple index of exposure based on distance from the source. These difficulties are associated with the low signal strength associated with public exposure, the contribution from

Year	Schools	Hospitals	Other	Maximum fraction of ICNIRP public reference level
2001	100	–	–	1/279
2002	82	27	4	1/731
2003 to date	38	3	–	1/1834
TETRA: 10 sites				1/336

Breakdown by exposure fraction decade						
	$> 10^{-2}$	$< 10^{-2}$–10^{-3}	$< 10^{-3}$–10^{-4}	$< 10^{-4}$–10^{-5}	$< 10^{-5}$–10^{-6}	$< 10^{-6}$
Excluding TETRA	–	11	93	105	37	8
TETRA: 10 sites	–	6	3	–	1	–

TABLE 2.10 *Radiocommunications Agency mobile phone base station audit summary*

other environmental sources of RF with similar field strength magnitude, and the variability in the local field strength that depends upon the call traffic. In addition, the propagation of fields to locations in homes is affected markedly by local perturbation. It has been concluded (Schüz and Mann, 2000) that this metric is a poor proxy taking into account the directional beam characteristics, the scattering, attenuation and reflection of the signal by houses, and the contribution from other sources. Spot measurements in homes are unlikely to be a good indicator of exposure over time in the light of time-dependent signal variability, the effect of signal attenuation by housing material, and the presence of other RF sources. One possibility of carrying out exposure prediction is the use of software tools owned by the mobile phone operating companies for the purposes of research.

Terrestrial and satellite microwave links (3–200 GHz)

69 Frequencies used by fixed-site telecommunications services range from the VLF band to the high microwave region. Services include public and private communications networks, satellite ground stations and control/telemetry services to remote sites. The majority of these are point-to-point microwave communications links, but the principles of exposure assessment would apply equally to mobile systems.

70 A summary of fixed microwave links is given in Table 2.11. Most of these systems use parabolic dish reflectors up to 3.7 m in diameter, mounted on towers or on buildings.

71 Satellite uplink services are detailed in Table 2.12. The Very Small Aperture Terminal (VSAT) systems are transportable. A theoretical assessment of the power density from a typical 14 GHz VSAT terminal has shown that the power density rises along the axis in front of the dish for about 40 m but then starts to fall off.

72 These systems generally use parabolic reflectors of circular cross-section with diameters varying from 1 or 2 metres to tens of metres with many falling in the range 5–15 m. Since these diameters are much greater than the 2 cm wavelength, the antenna gains are very large, ranging from 30 to 80 dB, so that line-of-sight communication is possible over large distances. The power output normally varies from less than a watt to a few watts but may be in excess of a kilowatt for satellite links. Various approaches have been used to estimate the potential exposure to fields from such antennas

TABLE 2.11 *Fixed microwave links in the UK*

Band (GHz)	Power to antenna (W)	Number of installations
1.7–2.45	5	250
4	20	1200
6	10	3000
7	–	500
11	10	1800
13	10	1500
15	3	500
18	0.4	1600
23	1	4500

TABLE 2.12 *Satellite TV uplinks*

Type	Band (GHz)	Power (W)	Dish (m)	Number
Broadcast uplink	14	600	3–5.5	12
VSAT	14	2–5	1.8	200

(Hankin, 1974; Ministry of Defence, 1989). Although, in principle, it is possible to be exposed to power densities of a few hundred W m^{-2} (a few hundred V m^{-1}) near these high power antennas, this is most unlikely to be the case for members of the public. The antenna is directed at a satellite so, since nearby buildings need to be avoided, exposure to the main lobe is unlikely to arise. Only people who have access to the vicinity of the reflector or approach the useful beam at low elevation angles are likely to be materially exposed and their exposure will be to fields around a few tens of W m^{-2}, below the ICNIRP reference level for occupational exposure (ICNIRP, 1998). Public exposure at normally accessible positions will be typically below 10^{-4} W m^{-2} (0.2 V m^{-1}) at distances in excess of 100 m measured along the axis of the dish.

Induction heating

73 RF induction heaters are used extensively in industry for a variety of purposes such as surface hardening, zone refining, annealing and brazing. The frequency and power used depend upon the process requirements but an important parameter in choice of frequency is the depth of penetration of the field or skin depth. The powers range from about 1 to 10 kW and the coils may be small, single-turn devices of a few cm diameter used for heating localised regions of a product to larger multi-turn systems.

74 Measurements of electric and magnetic field strength made on induction heaters operating in the frequency range from 395 kHz to 3.8 MHz (Cooper, 2003) are summarised in Tables 2.13 and 2.14.

Machine	Frequency (kHz)	Power (kW)	Reference level (V m^{-1})	Distance from unit (cm)	Electric field strength (V m^{-1})
1 (coil 1)	395	10	610	20 100*	100 30
1 (coil 2)	395	10	610	10 100*	300 20
2	2200	~1	277	10 30*	100 55
3	2400	~1	254	10 30*	100 55
4	3800	~1	161	10 30*	220 32
5	2550	~1	239	10 30*	45 < 10

TABLE 2.13 *Electric field strengths from induction heaters*

* Typical operator position.

75 At frequencies of 300 to 500 kHz, operator exposure to 16 induction heaters (Conover et al, 1986) of nominal RF output powers ranging from 2.5 to 50 kW, indicated that the magnetic field strengths were in the range < 0.08 to 17.6 A m^{-1}.

76 Measurements on ten heaters with powers ranging from 2.5 to 15 kW in the frequency range from 300 to 790 kHz (see Table 2.15) illustrate that fields can be highly localised. Coil impedance rises with frequency and, at frequencies of several hundred kHz and above, electric field strengths may become of greater relevance than magnetic fields when compared to exposure guidelines. In general, it is necessary to make measurements of both electric and magnetic field strength around LF, MF and HF induction heaters.

TABLE 2.14
Magnetic field strengths from induction heaters

Machine	Frequency (kHz)	Power (kW)	Reference level (μT)	Distance from unit (cm)	Magnetic field strength (A m^{-1})
1 (coil 1)	395	10	5.1	5 30 100*	336 14.4 2.8
1 (coil 2)	395	10	5.1	5 30 100*	384 27.2 0.6
2	2200	~1	0.91	10 30*	5.0 <0.3
3	2400	~1	0.83	10 30*	2.4 <0.3
4	3800	~1	0.53	10 30*	2.3 <0.3
5	2550	~1	0.78	10 30*	5.8 0.4
6	0.15	1500	167	–	40
7	0.15	1500	167	–	21.6
8	1	750	30.7	15 100 250 500	1360 240 64 13.6
9	436	7.5	4.6	5 20	59.2 2.0

* Typical operator position.

TABLE 2.15
Measurements at specific anatomical positions

Frequency (kHz)	Magnetic field strength (A m^{-1})			Electric field strength (V m^{-1})		
	Head	Hands	Abdomen	Head	Hands	Abdomen
484	1.44	–	1.68	650	8175	500
743	0.88	0.72	0.40	160	213	32
394	1.52	12.88	5.44	168	840	70
300	0.24	0.24	0.24	16	16	8
630	1.28	0.80	0.80	35	35	23
785	14.64	9.92	0.72	929	310	36
715	18.00	–	6.72	1583	–	326
790	7.04	8.64	1.2	413	722	16
434	20.48	20.48	14.64	1192	1828	646
500	8.48	–	3.52	192	–	64

77 Figure 2.11 shows the decrease with distance of electric and magnetic field strength from a 3.8 MHz induction heater. Figure 2.12 illustrates the non-uniform nature of the field distribution at positions occupied by an operator.

78 Measurements tend to be made at specific positions but the information on time spent by operators at these positions is limited. The rapid variation in field strength at close distances to small coils is an important factor in determining exposure.

79 Domestic and commercial cooking hobs have been developed using the induction heating principle, eddy currents being induced in pans using flat coils or rings placed beneath the pans. The frequencies used are in the 20–40 kHz range with powers usually ranging from about 1 to 5 kW. Measurements of electric and magnetic fields in the vicinity of such equipment under conditions of maximum power (Stuchly and Lecuyer, 1987; Allen et al, 1994) show that electric field strengths at distances of 25 and 30 cm can range from 4.3 to 50 V m^{-1} and magnetic field strengths from 0.7 to 3.8 A m^{-1} depending upon the circumstances of use, including the number of rings activated.

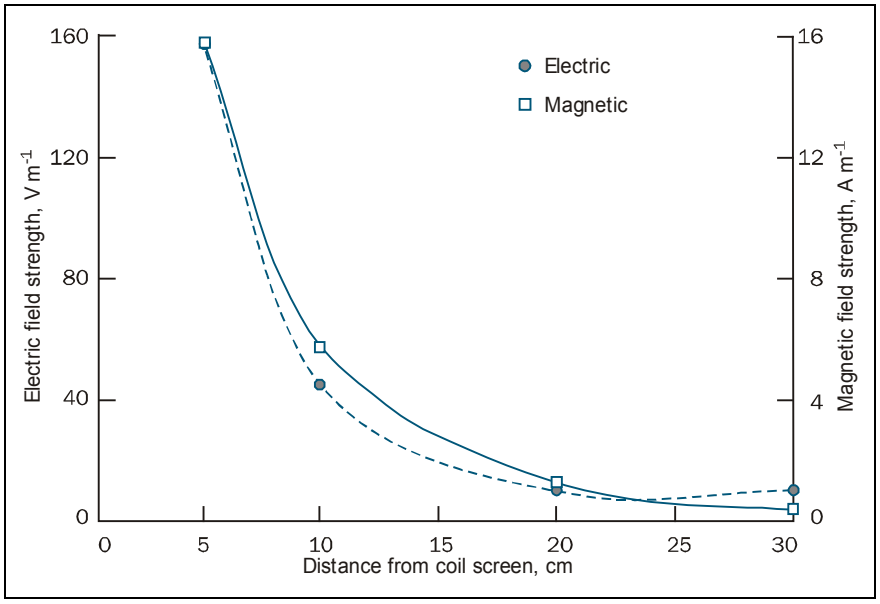


FIGURE 2.11
Fields with distance from a 3.8 MHz induction heater

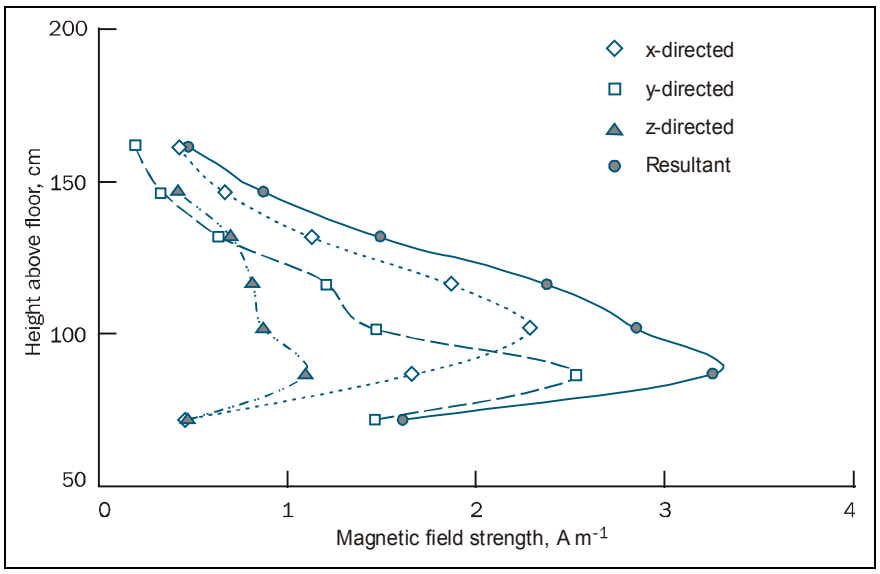


FIGURE 2.12
Magnetic field profiles at 70 cm from a 393 kHz induction bottle sealer

Plasma discharge equipment

Plasma etchers

80 Plasma etchers are used in various stages of the semiconductor fabrication process to break down polymer etch-resistant coating, etch metals deposited on the semiconductor wafer, or assist in building up deposits on the wafer through plasma-assisted chemical vapour deposition (PACVD). The technique involves the delivery of RF energy to a pair of electrodes inside an evacuated reaction vessel, in which the wafers to be etched are placed, in order to establish and maintain a plasma discharge.

TABLE 2.16 *Electric field strengths at specified distances from the reaction vessels of plasma etchers and chemical vapour deposition equipment*

Model	Frequency (MHz)	Power (kW)	Reference level (V m^{-1})	Distance (cm)	Electric field strength (V m^{-1})
1	13.56	–	61	10	10
2	13.56	0.74	61	10	7
3	13.56	0.8	61	5	2
4	13.56	0.2	61	5	< 0.5
5	13.56	0.5	61	5	< 0.5
6	0.28	0.5	610	5	< 0.5
7	13.56	–	61	2.5	2.7
8	13.56	0.06	61	5	< 20
9	0.375	1.5	610	5	< 0.5

TABLE 2.17 *Magnetic field strengths at specified distances from the reaction vessels of plasma etchers and chemical vapour deposition equipment*

Model	Frequency (MHz)	Power (kW)	Reference level (A m^{-1})	Distance (cm)	Magnetic field strength (A m^{-1})
1	13.56	–	0.16	5	< 0.05
2	13.56	0.74	0.16	5	< 0.05
3	13.56	0.8	0.16	5	< 0.05
4	13.56	0.2	0.16	5 20 30	1.54 0.28 0.07
5	13.56	0.5	0.16	20 30	0.16 < 0.05
6	0.28	0.5	5.7	5	< 0.08
7	13.56	–	0.16	2.5	0.006
8	13.56	0.06	0.16	5	< 0.05
9	0.375	1.5	4.3	5	< 0.08 *
10	13.56	0.45	0.16	5	< 0.03
11	13.56	0.1	0.16	5	< 0.03
12	13.56	2	0.16	5	0.06 †
13	13.56	0.4	0.16	5	< 0.03
14	0.38	1	4.2	5 20	13 0.5
15	0.14	130	11	5 10 30	50 8 2

* 7.2 A m^{-1} measured in small area where gas pipes enter casing.
† 1.63 A m^{-1} measured around the RF feed and matching unit when the screening panels were removed.

81 Measurements of electric and magnetic field strength close to plasma etchers and PACVD equipment and measurements of contact current from the surfaces of reaction vessels have been made (Cooper, 2003) and the results are given in Tables 2.16 and 2.17. The recorded electric and magnetic field strengths are representative of the maximum values at the specified distances from the reaction vessels. Measurements of field strength a few centimetres from the vacuum chambers represent hand exposures; exposures of the head or torso are indicated by measurements at greater distances.

RF sputterers

82 RF sputterers are similar to plasma etchers in that the process applies coatings to components placed inside an evacuated chamber by means of a plasma discharge. Measurements of electric and magnetic field strength have been made close to the vacuum chambers and control/matching units of four sputtering units operating at 13.56 MHz; the results are reported in Tables 2.18 and 2.19.

83 It is unlikely that parts of the body such as the head or torso would be substantially exposed at the closest measurement distances given in Tables 2.18 and 2.19.

Model	Power (kW)	Distance (cm)	Electric field strength (V m^{-1})
1	3.6	5	150
		15	22
2	3.5	3	280
		10	10
		20	< 61
3	3.5	3	180
		10	61
		30	< 27
4	0.08	5	< 0.5

TABLE 2.18 *Electric field strengths from 13.56 MHz RF sputtering units*

Model	Power (kW)	Distance (cm)	Magnetic field strength (A m^{-1})
1	3.6	5	0.53
		15	0.12
2	3.5	10	> 1.10
		30	0.40
		50	0.16
3	3.5	10	0.16
		30	< 0.07
4	0.08	5	< 0.05

TABLE 2.19 *Magnetic field strengths from 13.56 MHz RF sputtering units*

Plasma torch

84 Plasma torches are used as part of mass spectrometry systems. The torch assembly comprises a glass cylinder that contains the discharge electrodes. The coaxial coil was excited by a 27 MHz RF signal with an operating power of 1.4 kW – the electric and magnetic field strengths measured at various positions of the torso are given in Table 2.20.

Security and access control

85 Under the general heading of security and access control, there are three broad types of equipment that generate RF fields. These are metal detectors, electronic article surveillance (anti-theft devices) and RF identification (RFID) systems.

TABLE 2.20
Electric and magnetic field strengths around a plasma torch

Operating conditions	Region of exposure	Electric field strength ($V\ m^{-1}$)	Magnetic field strength ($A\ m^{-1}$)
Inner and outer shields removed	Hands Head Torso	316 30 30	2.2 0.14 0.25
Inner shield in place, outer shield removed	Hands Head and torso	– < 30	0.22 < 0.07
Inner and outer shields in place	All exposures	< 30	< 0.07
Reference level	–	61	0.16

Metal detectors

86 Metal detectors are to be found in airports, prisons and other high security areas. The detectors can be of the walk-through type or handheld units for close body inspection.

Walk-through detectors

87 Walk-through detectors are usually configured as an arch with the vertical pillars containing the pulsed magnetic field coil generator and the receiver which detects currents induced in metal by the transmitter. Typically the pulses exhibit bipolar pulses which, when analysed, demonstrate broad spectral content peaking in the kHz frequency range.

88 Figure 2.13 shows an example of a waveform of the magnetic field emitted by a walk-through metal detector. Table 2.21 gives measurements of peak magnetic field strength measured on two such metal detectors.

FIGURE 2.13
Magnetic field waveform from a walk-through metal detector

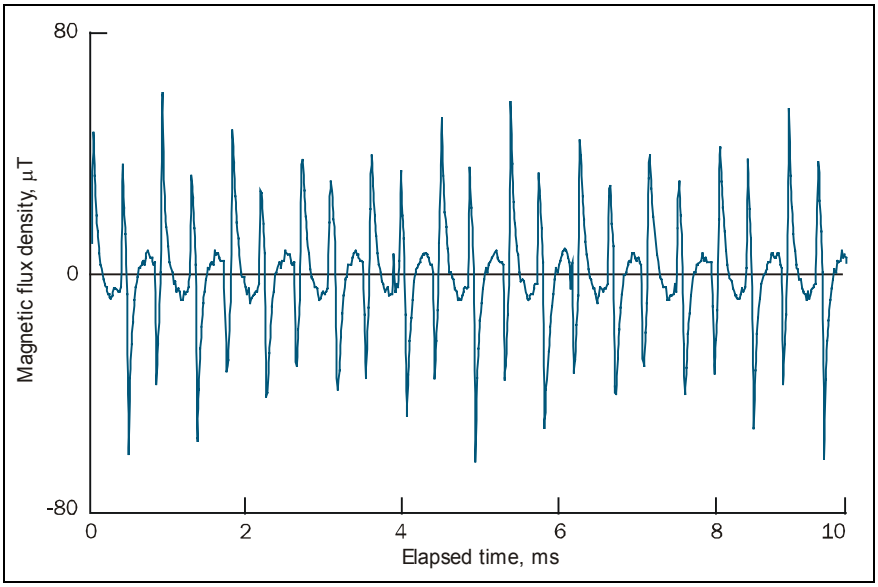


TABLE 2.21
Exposures from walk-through metal detectors

Metal detector	Peak magnetic field strength ($A\ m^{-1}$)
1	75
2	84

Handheld metal detectors

89 The alternating current in the coils in handheld devices is often in the kHz frequency region. Eddy currents produced in nearby metal disturb the magnetic fields produced and lead to a change in the coil's frequency response, which is detected.

90 Examples of the magnetic field strengths generated by two metal detectors are shown in Table 2.22.

Metal detector	Peak magnetic field strength, 2.5 cm from casing (A m^{-1})	Frequency (kHz)
1	25	20
2	4	94

TABLE 2.22 *Exposures from handheld metal detectors*

Electronic article surveillance

91 Electronic article surveillance (EAS) equipment is used to prevent theft from establishments such as shops and libraries. EAS systems comprise a detection unit, a tag to be detected and sometimes a tag deactivator. The principles of operation are similar to those of metal detectors and RFID systems in that an electromagnetic field is produced over a defined volume. If a tag that has not been deactivated, or removed from the item to which it is attached, enters the detection region, the resulting characteristic perturbation of the field is detected. As with RFID systems, a broad range of frequencies is used by different types of EAS equipment from sub-kilohertz frequencies to microwave frequencies.

92 EAS detectors typically contain two or more elements for the generation and detection of fields, which have the appearance of flat panels, loops or pillars and are positioned either side of the customer exit of the shop or library, etc. At least one of the elements contains transmitter coils; the other element or elements contain receiver coils, and possibly transmitter coils too if a Helmholtz configuration is employed. Systems also exist that employ just a single antenna containing coils that are connected to the transceiver.

93 Deactivators are generally desktop devices installed at the customer checkout. Disposable tags containing resonant circuits may be deactivated by overloading the circuit using a pulsed RF magnetic field at the resonant frequency.

94 Measurements of electric and magnetic field strength close to EAS equipment and of contact current from some devices have been carried out; the results are summarised in Tables 2.23 and 2.24. The field strength values given in these tables are the maximum ones measured at a given distance from the device. In the case of exposures to pulsed fields, the displayed field strengths are the maximum rms field strengths during a pulse.

Dielectric heating (10–100 MHz)

95 Machines used for RF dielectric heating have been identified as potentially one of the most important sources of RF exposure amongst the working population and have been the focus of some attention (Conover, 1980; Erikson and Hansson Mild, 1985; Bini et al, 1986). The wavelength range in air of this type of equipment is 3–30 m, thus exposure occurs well within a wavelength of the source where complex field distributions occur. Dielectric heaters have output powers ranging from less than a kW to tens of kW and can be completely shielded and automated or be unshielded and operated manually.

TABLE 2.23
Electric field strengths from EAS detectors and tag deactivators at specified distances from the plane of the antenna casing of each device. The detectors were dual antenna systems unless noted otherwise

Device	Frequency (MHz)	Transmission characteristics	Distance (cm)	Electric field strength (V m^{-1})
Detector	7.4–9.1	Continuous, swept frequency	10	4.0
Detector (single antenna)	7.4–8.8	Continuous, swept frequency	2.5	< 1
Detector	7.4–8.8	Continuous, swept frequency	2.5	< 1
Deactivator (detection mode)	7.4–8.6	Pulsed, frequency stepped	10 20	89 21
Deactivator (detection mode)	7.4–8.8	Continuous, swept frequency	2.5	< 1
Deactivator (deactivation mode)	7.4–8.6	Pulsed, fixed frequency	10 20	86 20
Deactivator (deactivation mode)	7.4–8.8	Pulsed, fixed frequency	5 10 20	190 60 9

TABLE 2.24
Magnetic field strengths from EAS detectors and tag deactivators at specified distances from the plane of the antenna casing of each device. The detectors were dual antenna systems unless noted otherwise

Device	Frequency (MHz)	Transmission characteristics	Distance (cm)	Magnetic field strength (A m^{-1})
Detector	0.001953	Pulsed, fixed frequency	25 100	350 30
Detector	7.4–9.1	Continuous, swept frequency	15 20	0.09 0.06
Detector (single antenna)	7.4–8.8	Continuous, swept frequency	0 10 20	2.0 0.39 0.18
Detector	7.4–8.8	Continuous, swept frequency	15 35	0.12 0.03
Deactivator (detection mode)	7.4–8.6	Pulsed, frequency stepped	3 10 50	12.3 3.1 0.18
Deactivator (detection mode)	7.4–8.8	Continuous, swept frequency	2.5	0.12
Deactivator (deactivation mode)	7.4–8.6	Pulsed, fixed frequency	3 10 30 50	58 2.7 0.34 0.13
Deactivator (deactivation mode)	7.4–8.8	Pulsed, fixed frequency	5 10 20	10 3 0.8

In general, the greatest exposure arises from machines of a few kW used for welding PVC where, in particular, operators of machines using C-frame presses to weld PVC often sit 30–50 cm from the welding electrodes.

96 Electric field strengths can be up to 500 V m^{-1} at the positions of the torso, and hands may be placed in regions where the field strength exceeds 1 kV m^{-1}. Magnetic field strengths vary from less than 80 mA m^{-1} to about 0.4 A m^{-1} at the position of the torso, whereas the hands may be transiently exposed to fields around several A m^{-1}.

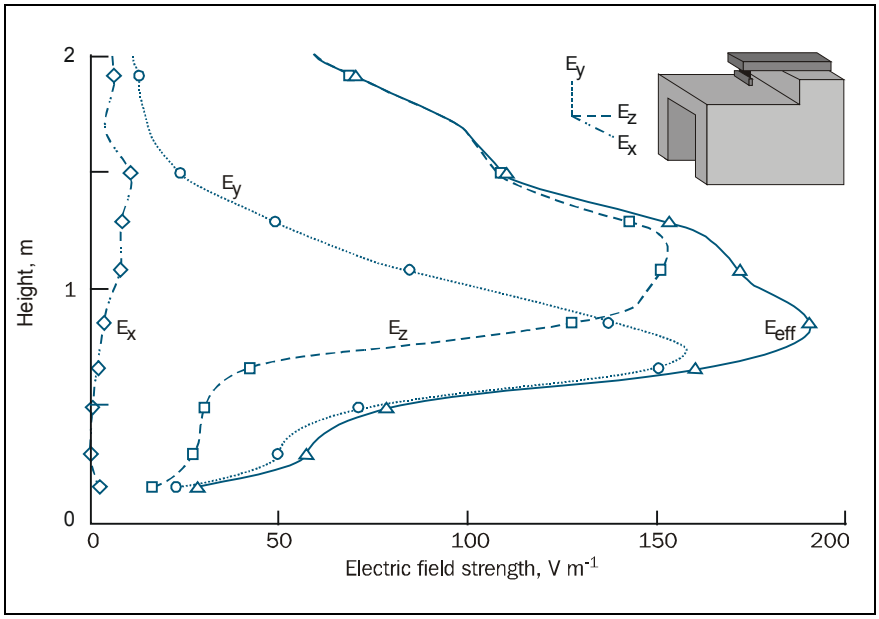


FIGURE 2.14
Electric field strength distributions near a 27.12 MHz PVC welding machine

97 The RF grounding of the frame of the machines can substantially affect the current distribution on the machine and therefore the magnetic field generated. In addition, the spatial distribution of electric field strength at positions occupied by the operators is highly non-uniform, resulting in a reduced energy absorption rate in the near-field. Figure 2.14 illustrates a typical electric field strength profile.

98 The problems of evaluating exposure to this type of equipment are complicated by the nature of the work. The weld cycle is usually a matter of seconds and the duty factor (RF on time to total cycle time) can vary from about 0.1 to 0.5. During each weld cycle the field strengths vary and the operators may need to place their hands in regions of high field strength.

99 At the frequencies used for RF dielectric heating it is possible to obtain a measure of the currents induced in the body resulting from exposure to the electric fields (Allen et al, 1986; Conover et al, 1992). The development of approaches using induced current provides an improved indicator of exposure. Table 2.25 gives the currents measured by NRPB for a variety of machines.

Diathermy

100 Short-wave and microwave diathermy is used as an adjunct to physiotherapy to alleviate acute or chronic conditions of the muscles, ligaments, tendons and joints by heating tissue using RF energy. The consequence of this tissue heating is stimulation of the blood supply and enhanced metabolism in the treated area.

101 The levels of electromagnetic energy required to achieve desired localised temperature rises exceed those set down in current safety standards. In the case of the patient it is expected that there will be a net benefit.

102 Some of the RF energy may be scattered and possibly absorbed by the operator. In the case of directed microwave energy it is possible that part of the useful beam, which does not irradiate the patient, could be intercepted by the physiotherapist.

TABLE 2.25 *Electric and magnetic field strengths and currents induced in operators seated at PVC welding machines*

Frequency (MHz)	Power (kW)	Ground	E_{max} (V m^{-1})	H_{max} (A m^{-1})	Duty cycle factor (DCF)	Operating ankle current (mA)		Non-operating ankle current (mA)	
							DCF corrected		DCF corrected
27	–	Rubber/concrete	280	–	0.3	84	46	79	43
27	3	Concrete	280	0.45	0.3	270	148	280	153
27	3	Concrete	212	–	0.3	85	47	55	30
27	1	Concrete	40	–	0.5	18	13	17	12
27	1.6	Concrete	150	0.16	0.3	100	55	–	–
28	15	Concrete	316	–	0.5	70	49	70	49
29	3	Wood/ concrete	37	–	0.2	27	12	19	8
36	1.6	Rubber/concrete	30	–	0.5	17	12	13	9
45	7	Concrete	100	–	0.16	60	24	60	24
50	3	Concrete	113	–	0.13	190	69	120	43
51	7	Wood	100	–	0.2	37	17	37	17

Short-wave diathermy

103 In the case of short-wave diathermy equipment the electrodes are 'close coupled' to the treatment area (Table 2.26). Nonetheless, stray leakage fields will be present in the region of the applicator and from the supply leads.

TABLE 2.26 *Fields from short-wave (27.12 MHz) diathermy equipment*

Reference	Position	Electric field strength (V m^{-1})	Magnetic field strength (A m^{-1})
Hansson Mild, 1980	1.7 m – 0.6 m from electrodes	43–600	0.12–1.2
	1 m from electrodes	270	0.32
	1.5 m – 0.35 m from leads	–	0.12–1.2
	1.5 m – 0.5 m from leads	43–430	–
Stuchly et al, 1982	0.2 m from electrodes	80– > 1000	0.3–2.0
	0.4 m from electrodes	40–500	0.2–0.8
	0.6 m from electrodes	20–160	0.1–0.6
Martin et al, 1990	0.2 m from electrodes	45–5000	0.03–11
	1 m from electrodes	3–90	0.002–0.6

Microwave diathermy

104 The frequency used for microwave diathermy is 2450 MHz. Typically the operating power of such equipment is around 200 W and energy is directed to the patient using reflector-type antennas, but the design and field characteristics of each type of applicator vary considerably. Power densities measured at distances varying from 0.3 to 1.2 m from five different applicators ranged from 0.3 to 100 W m^{-2}. Power densities can exceed reference levels close to applicators. On the basis of stray field measurements made on available microwave equipment, parts of the body may be exposed transiently to power densities in excess of 50 W m^{-2} if the operator is in front of the plane of the front surface of the applicator.

Visual display units (VDUs) (15–30 kHz and harmonics)

105 Visual display units used as computer displays are found in virtually every workplace and in many homes, the principal difference between VDUs and televisions that generate similar fields being the generally closer distance of people to VDUs. In addition to static electric fields, electric and magnetic fields are produced in the ELF and VLF bands from the power supply and the line-scan and screen refresh generators. There have been a number of studies quantifying the exposure to these fields (AGNIR,1994). Radiofrequency fields in the VLF range are generated by the horizontal deflection coils with a line-scan frequency typically from 15 to 35 kHz with harmonics up to several hundred kHz. Measurements made at operator positions about 30–50 cm from the screen indicate that the ELF and VLF electric field strengths are in the range 1–15 V m^{-1}, although close to the surfaces of the equipment field strengths may be 200–300 V m^{-1}. The VLF magnetic field strength at operator distances is in the range 4–480 mA m^{-1}, although most exposures are below 160 mA m^{-1}. ELF magnetic flux densities tend to be higher by a factor of two or more. Close to the VDU cases, VLF magnetic field strengths can be several A m^{-1}. Product emission standards are based on technically achievable values rather than on the basis of safety considerations; however, exposure levels are considerably lower than those suggested in current guidelines.

Microwave ovens (2.45 GHz)

106 Microwave ovens are manufactured to standards, which require that leakage levels are kept below emission limits. In the UK, the relevant British Standard EN 60335-2-25 (BSI, 1997) requires that microwave leakage should not exceed 50 W m^{-2} (140 V m^{-1}) at 5 cm from the external surface of the appliance.

107 Since this value is greater than the ICNIRP reference level for the public of 10 W m^{-2} (ICNIRP, 1998), it is important to note that if leakage occurs, it is normally from a small area such as a slot in the region of the oven door. The emission from this small slot spreads out and also falls off rapidly so that while the power densities near to the slot may be quite high, they will be very much lower in regions occupied by people.

108 In a UK catering industry survey of 357 microwave ovens, of which 208 were of the domestic type, 6 ovens indicated leakage above 10 W m^{-2} and 1 oven did not meet the 50 W m^{-2} emission standard (HSE, 1989). Leakage of 10 W m^{-2} at 5 cm from a small area resulted in exposures of 0.1 W m^{-2} at 50 cm and 25 mW m^{-2} at 1 m, both well below the reference levels. In practice, therefore, the British Standard for the product should provide adequate protection for the consumer. A study carried out in Germany on 130 microwave ovens in domestic use found that all of the ovens tested were below an emission level of 10 W m^{-2} (Matthes, 1992). Statistical analysis suggested that about 0.005% of ovens might exceed 50 W m^{-2}. The ovens ranged in power from 350 to 1200 W and varied in age from less than 1 year up to 18 years and were used from less than 15 minutes to 75 minutes. There was no clear dependence of microwave leakage on any of these parameters.

Radar

109 The term radar covers a wide range of applications from low power doppler systems to large air and space surveillance systems. The majority of radars operate in the UHF and SHF regions and most employ pulsed transmissions with duty cycles in the range 0.0001–0.01, and pulse lengths of the order of microseconds. Most radars employ highly directive, high gain antenna systems.

110 It is possible to calculate the on-axis peak and average power densities of a radar system. Table 2.27 illustrates the application of such calculation techniques applied to two systems. It can be seen that the power density in the near-field of the tracking radar is higher, because of the smaller antenna aperture, even though it is a lower power system.

TABLE 2.27 *Typical characteristics of two radar systems*

Parameter	ATC radar	Tracking radar
Wavelength	23 cm	3 cm
Peak power	2.3 MW	200 kW
Average power	3.4 kW	300 W
Aperture	10 m	1 m
Near-field boundary	154 m	12 m
Distance to 100 W m^{-2}	132 m	33 m
Distance to 10 W m^{-2}	553 m	102 m
Maximum power density in near-field	173 W m^{-2}	1528 W m^{-2}

Air traffic control

111 Responsibility for civil air traffic control (ATC) radars within the UK is undertaken by National Air Traffic Services (NATS). This includes primary (surveillance), approach, ground movement and secondary (transponder) radars. A summary of civil ATC radars is given in Table 2.28.

112 For most radar systems there is a high peak power in the pulse compared with the average power determined from the pulse repetition rate and pulse width. In addition to the reduction in average power due to the pulse characteristics, surveillance radar systems such as ATC frequently use a narrow beam of only a few degrees (typically about 3°) which is rotated several times per minute and this reduces the average power by a further factor. The beams are highly directional and, outside the main beam, the power density decreases by several orders of magnitude. Measurements at several hundred metres from such systems indicate average field strengths of tens of mV m^{-1} (around 10^{-5} W m^{-2}) and peak field strengths of several V m^{-1} (around 10^{-1} W m^{-2}).

113 At an ATC test facility with the antenna stationary, NRPB has made measurements in the vicinity of a radar operating at a frequency of 2.8 GHz and peak power output of 650 kW. At ground level between 100 and 250 m from the antenna and in the equipment cabin at a height of 9 m above the ground and 60 m from the antenna, electric field strengths were less than 14 V m^{-1} (0.5 W m^{-2}). At about 19 m from the antenna the power density at a height of 9 m above ground was 87 V m^{-1} (20 W m^{-2}). Under normal operating conditions with the antenna rotating, the time-averaged power density would be considerably lower.

TABLE 2.28 *UK air traffic control radars*

Operating wavelength (cm)	Radar type	Maximum peak power (kW)	Maximum average power (W)	Number of units
50	S264	70	150	5
50	S264A	500	1000	9
23	HSA/ARJ	75–2200	120–3300	12
10	Various	60–650	125–600	43
3	Various	20–150	10–230	38
2	ASTRE	20	6.5	3

Traffic radar

114 Radars for traffic speed assessment generally use frequencies of around 10.5 or 24 GHz, although some operate at about 35 GHz. The radars operate under continuous wave conditions using the doppler frequency shift of the reflected signal created by a moving object. The powers used by the radars are in the 10–100 mW range and measurements summarised by NIOSH of several investigators (Lotz et al, 1995) for both fixed and handheld systems indicate that the power densities measured at 5 cm from the radar apertures range from 1.4 to 64 W m^{-2}. The mean power density measured by NIOSH was about 10 W m^{-2} and exposures outside the 30° cone from the antenna aperture less than 0.1 W m^{-2}.

SUMMARY AND CONCLUSIONS

115 Equipment designed for making spot measurements (point in time, point in space) of electric and magnetic fields around RF sources has been available for many years. The literature contains measurements near to many different types of sources and, generally, the data are compared with the reference levels in guidelines for limiting people's exposure. Sometimes the spot measurements are analysed further to take account of time and spatial variations in the electromagnetic field, particularly where spot measurements show the presence of fields approaching the ICNIRP reference levels.

116 Often the fields around RF sources reduce rapidly with increasing distance, with the result that exposure of people near a source depends strongly on their location and orientation. Also, superficially similar sources often operate at different frequencies and power levels, and may have different electrical configurations. These considerations are reflected in the wide range of field strengths reported in the literature around apparently similar sources and mean that any use of published data must carefully consider the detailed characteristics of the source and how the measurements were made.

117 More recently, body-mounted electric and magnetic field sensing instruments incorporating data-logging capabilities have become available and these allow the exposure of a person to be sampled at short time-intervals over an entire working shift. The equipment measures field strengths near the surface of the body at the point where the meter is worn, but caution is required in their interpretation. These fields are different to the fields that would be present when the body is absent and do not readily provide information that reflects spatial variations over the body surface. Consequently, such instruments are not sufficient on their own for ensuring compliance with exposure guidelines. Nevertheless, the information they provide may be helpful in obtaining broad estimates for ranking exposures in an epidemiological context.

118 The link from field strengths produced outside the body to those produced inside the body is not straightforward for RF fields. However, considerable advances in understanding have been made in recent years through the development of computational dosimetry and anatomically realistic numerical phantoms. In principle, it is possible to calculate the precise distribution of field strengths inside the body for a given situation, but where a person is moving, the number of different situations to be considered in order to predict exposure over time rapidly becomes too great.

119 Modern digital radio devices such as mobile phones and wireless LANs tend to operate at much lower power levels than industrial equipment, but they can be used much closer to the body, eg 2 cm in the case of the phone. Where devices are used so close to the body, it is not practical to relate the fields produced outside the body to those produced inside. Instead, internal fields are measured directly inside physical models of the body, known as phantoms, or calculated using numerical models of both the RF device and the body considered as a coupled entity.

120 There are few situations where the general public is likely to be exposed to fields that exceed the reference levels contained in current exposure guidelines. Where such cases do arise, and for some occupational exposures where there is a greater likelihood of exceeding reference levels, dosimetric approaches using physical and numerical modelling are required to establish whether or not the basic restrictions on exposure are met.

121 Measurements made by the Radiocommunications Agency and NRPB of exposures to RF radiation of members of the public near to mobile phone base stations have continued to demonstrate that exposures are generally extremely small fractions of guideline levels.

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3 Cellular Studies

1 The scope of this chapter has mainly been limited to new evidence published since the IEGMP report in 2000.

2 Studies of cellular or *in vitro* systems have some major advantages over animal or human studies. *In vitro* investigations are useful as they study simplified systems and allow the radiofrequency (RF) exposure and the biology to be more precisely defined and controlled. This approach has the benefit that it can produce rapid results and give an insight into possible mechanisms involved in the interaction. However, these studies have their limitations. The main disadvantage in investigating isolated cells or systems is that they do not take into account the many interactions that would normally take place in a whole organism.

3 Cells continually respond to their environment, but problems may occur when the normal physiological conditions are exceeded and the cells are pushed beyond their capability to adapt. Even then, adverse cellular changes may not be harmful to the whole organism as there are naturally occurring protective and repair mechanisms. Hence a cellular change does not imply an effect on the whole organism and neither is the same as a health effect.

4 A major area of public concern is the possibility that RF radiation from mobile phones and base stations is carcinogenic. Carcinogenesis at the cellular level is a multi-stage process and if RF exposure is involved it would have an effect on one or more of these cellular stages. Most of the known carcinogens, but not all, are genotoxic, ie they cause DNA or chromosomal damage. Therefore if RF radiation were carcinogenic it could possibly also have genotoxic effects on cells. Many studies are devoted to testing for genotoxicity and use a range of *in vitro* tests to investigate this possibility. Several studies also test the possibility that RF radiation acts synergistically with other known carcinogenic agents to enhance or promote their effect.

5 One advantage of *in vitro* systems is that the exposure conditions can be controlled and more easily defined than in animal or human studies. Most experimental studies use purpose-designed exposure systems in which the relevant parameters can be selected or measured. However, an important parameter, the specific (energy) absorption rate (SAR), can only be measured indirectly or calculated. The pattern of SAR distribution can vary substantially within an exposure system and no system provides a completely uniform distribution when there are cells present. The type of exposure system – for example, TEM cell or waveguide – will have a major influence on the overall uniformity of SAR distribution, but other factors such as the geometry of the container enclosing the cells and even the presence of a meniscus will alter the pattern of SAR distribution. Thus in any exposure system the cells will receive a range of SAR values. In addition, if a pulse modulated signal is applied the cells will only receive an exposure during the pulse. For GSM signals the pulse cycle is one in eight, so that the cells will only be exposed to RF radiation for 1/8th of the total exposure time and the mean SAR will be 1/8th of the peak SAR.

6 As a general guideline, experiments in which the exposure to RF radiation has an SAR of less than 1 W kg^{-1} are less likely to involve significant heating of the cells. Heat is

known to cause many biological changes and the heating effect of RF radiation is well established. However, there are claims that RF radiation could have non-thermal effects on biological systems. Hence the exposure conditions used in the experiments become very important to try to establish the difference between thermal and non-thermal effects. Some papers only quote the RF exposure as a power density. This is not necessarily a good indicator of the energy that the cells absorb, as similar power densities can give rise to markedly different SARs depending on the exposure system employed. The better experiments have good dosimetry, thus allowing the exposure to be properly assessed; they also have appropriate experimental controls, so that the size of the cellular response to RF radiation can be compared with known cellular stimulators or inhibitors. Unfortunately some of the papers, particularly those claiming positive effects, can be criticised for poor dosimetry and inadequate experimental controls.

7 The *in vitro* biological changes of RF exposure reported so far are relatively small, which makes experimental confirmation difficult. Even if these changes were confirmed the health implications would be difficult to assess and would require further studies with whole organisms. However, the results from *in vitro* studies can suggest possible mechanisms and indicate areas for further research.

INTERACTION OF RADIOFREQUENCY FIELDS WITH TISSUES

Theoretical mechanisms

8 The thermal and non-thermal effects that may result from the RF electric and magnetic fields produced in the body by an electromagnetic source were reviewed by IEGMP (2000, Sections 5.7–5.21) and the present discussion is largely concerned with papers that have been published since. It does not include analyses that have been made of the electric field distribution at the cellular level, although these are evidently very important in quantitative discussions of interaction mechanisms.

9 Thermal effects from RF electric fields occur because most biological tissue is electrically conducting. Electric fields inside the tissue generate currents and their dissipation leads to energy absorption and hence to increases in temperature. Since many biochemical reactions are known to be strongly dependent on temperature, it seems plausible that temperature changes should give rise to biological effects. There seems to be general agreement though that it is unlikely for adverse health effects to arise from heating when the power absorbed is less than the ICNIRP guideline values (ICNIRP, 1998).

10 Non-thermal effects are effects that could arise through the many other interactions that take place between an electric field and the various components of biological material. The present review extends to very much greater frequencies than the IEGMP review but, even at the highest frequency considered of 300 GHz, the energy quantum is still only 1.2 meV, about 1000 times less than the energy needed to break the weakest chemical bonds in genetic molecules (DNA). However, a number of other possible processes have been discussed. Most of these would not appear to be strongly dependent on frequency.

11 One approach that has been considered by three groups is that RF radiation may cause changes in protein conformation (Bohr and Bohr, 2000a; Laurence et al, 2000,

2003; Astumian 2003). A molecular chain such as a protein can adopt many different conformations, each of different dipole moment and energy. Bohr and Bohr suggested that some of the conformations would have similar energies with relatively weak potential barriers between them. These conformational states could therefore interact to form a set of coupled states separated by energies corresponding to frequencies estimated to be around a GHz. Allowing for broadening, transitions between them could be produced by exposure to RF radiation over a range of frequencies in the GHz range. The transitions would result in changes in protein folding (denaturation) and so give rise to biological effects. The theory is at an early stage and does not include an explicit calculation of the strength of interaction with the external field nor does it consider dissipative effects such as viscous damping. Hence it is not possible to estimate the size of RF field required to produce a significant effect in the presence of thermal agitation.

12 The approach used by Laurence et al (2000) was rather different. Their analysis suggested that conformational changes occurred on a time scale sufficiently long (around 1 μs) for the protein to remain in thermal equilibrium with its surroundings. The suggested changes might be induced by transient increases in the local temperature. The authors argued that, at low powers, these conformational changes could lead to biological effects but that, at somewhat higher powers, these would be suppressed by the activation of a heat shock protein. Their conclusions were, however, significantly modified in a second paper (Laurence et al, 2003) which noted that the value used for the heat capacity of biological tissue in the first paper was too small by a large factor and that, in fact, the temperature rises were too small to produce conformational changes.

13 The mechanism considered by Astumian (2003) concerned conformational changes in the ATPases associated with ion channels (structures responsible for ion movement that span the membrane). The author concluded that this approach could have accounted for the observation of ion pumping across membranes produced by RF fields (Xie et al, 1997). The theory did not discuss the field strengths required to produce measurable effects but the experiments suggested they would lie above guideline levels even at frequencies below 1 MHz. At higher frequencies the effect of membrane capacitance results in a fall in the field within the membrane.

14 The observation by several groups of the expression of heat shock proteins by RF radiation (paragraphs 49–56) has provided some experimental support for conformational changes. It should be noted though that the experimental conclusions are not unanimous and by no means consistent. One further study has been reported on potential mechanisms: an investigation by de Pomerai et al (2003) of the aggregation of bovine serum albumen in solution when exposed to a 1 GHz signal for 3 to 48 hours with a peak SAR of 50 mW kg^{-1}. Aggregation occurs when partially unfolded proteins collide. Hence an increase in unfolded protein produces an increase in aggregation, which can be measured by means of changes in light scatter. At 25 °C there was a 5% increase in light scatter over a 48-hour exposure, showing an increase in aggregation and hence implying an increase in protein unfolding. It would be interesting to know how this modest change in light scatter translates into a percentage of the total protein being denaturated.

15 There has also been further discussion of the role that might be played by resonant absorption of RF energy by the vibrational states of biological components such as microtubules. Interaction between neighbouring biological components could in

principle broaden these states into bands just as interaction between atoms in a solid leads to bands of electronic states. This possibility was explored by Fröhlich (1968) and was the basis of a model of which one suggested outcome was that relatively weak RF signals could be amplified and produce significant biological effects (IEGMP, 2000). An essential requirement of the model is that the vibrational states have narrow widths – narrower in energy than the rather weak interaction between neighbouring states. This possibility has recently been examined by two groups (Foster and Baish, 2000; Adair, 2002). The main contribution to the width of the vibrational states seems likely to arise from the fact that the biological components are immersed in a viscous fluid. To estimate the effect of this, Foster and Baish calculated the relaxation time of the longitudinal oscillations of a cylinder immersed in water. For a cylinder with a diameter equal to that of a microtubule, the relaxation rate and hence the line width was around 1000 times larger than the frequency even at 10 MHz and would be even greater at higher frequencies. Similar conclusions were reached by Adair (2002). Both these calculations were for rigid cylinders and so do not represent well the modes of microtubules which include interface modes with amplitudes that in the absence of damping would decay exponentially into the fluid (Sirenko et al, 1996). However, since the fluid motion is damped in a distance less than this decay length, it seems very likely that these interface modes would also be heavily damped. It would appear then from this work that the widths of the vibrational states are too large for the formation of the bands required by the Fröhlich model.

16 Adair (2002) also calculated the energy that could be transferred to a vibrational state (mode) of a biological component from an electromagnetic field. The interaction is weak and, in fact, in the absence of damping, is forbidden by momentum conservation. Damping progressively removes this constraint but, since it also results in power being lost to the surroundings, it limits the energy transferred into the vibrational states. For DNA molecules assumed to have a vibrational state at around 10 GHz, Adair estimated that incident microwave power of 100 W m^{-2} increased the energy of the state from its thermal equilibrium value of $k_B T$ by 3 10^{-9} $k_B T$ (where k_B is Boltzmann's constant and T is temperature in kelvin). He concluded that this was far too small to produce significant biological effects and that this would remain the case even if the state were less strongly damped by its surroundings than expected from conventional arguments.

17 It has been suggested that resonant excitation of plasma-like collective modes within the high mobility quasi two-dimensional charge layers on membrane surfaces might provide a mechanism for RF absorption (Krasil'nikov, 1999). For hydrogen ions, the modes were calculated to have frequencies of around a GHz and estimates of their lifetimes indicated the modes might be moderately well defined. Interaction between cells of similar size and therefore frequency was suggested as a way in which biological effects might occur but no comparisons were made between the likely size of the interaction and thermal energies ($k_B T$).

18 The effect of RF radiation on ligand (eg Ca^{2+}) binding to cell receptor proteins has been considered by Chiabrera et al (2000). Their calculations suggested that significant changes in binding probability could occur at relatively low intensities should the RF energy quantum match the depth of the potential energy well. This assumes, however, that the RF desorption rate is comparable with the relaxation rate back to equilibrium which is by no means evident. Changes in the binding probability of Ca^{2+}

have also been considered by Thompson et al (2000), though using a model in which the RF radiation triggers a phase transition involving a large number of Ca^{2+} sites. Their approach was based on statistical mechanics and, since no description of the interaction mechanism was provided, it is not possible to estimate the size of RF fields that would be needed. The authors suggested, however, that the approach was consistent with the existence of the 'power windows' reported in some of the early experimental work on the rate of loss of calcium-45 (efflux) from brain tissue (see paragraphs 60–65). No comparisons were made between the likely size of the interaction and thermal energies.

19 In general, the interaction of RF magnetic fields with tissue would be expected to be very much weaker than RF electric fields. Possible exceptions might be expected to include interaction with tissue, including human brain tissue, containing particles of magnetite (Fe_3O_4). It has been suggested that the RF magnetic fields could interact either by ferromagnetic resonance or by mechanical activation of cellular ion channels, although it would be expected for the interaction to be suppressed by the slow orientation rate of the particles. Initial experiments on a bacterium containing magnetite, *M Magnetotacticum,* of the effect of the emission from a 900 MHz GSM handset placed above the sample (Cranfield et al, 2003a) suggested that RF exposure significantly increased the proportion of cell deaths (the exposure was for 16 minutes but no further details were given). However, the effect did not occur in later experiments (Cranfield et al, 2003b) in which the sample was exposed to 1800 MHz GSM radiation in a waveguide (SARs up to 2 W kg^{-1}). Since the exposure from the handset also included low frequency magnetic fields, the authors suggested these might have been the cause of the increase in cell deaths seen in their first experiments. Experimental results supported by theoretical analysis (Woodward et al, 2001) have suggested that RF magnetic fields can also influence chemical reactions through a mechanism involving radical ion pairs. This can apparently occur even when the magnetic interactions per molecule are much smaller than thermal energy. The measurements were made in the frequency range 1–80 MHz and the authors suggested that similar effects might occur in certain biomolecules.

20 In view of the attention given to the possibility that pulsed RF fields might interact differently with biological components from continuous wave RF fields, it is surprising that there has been almost no discussion of how this might arise. Pulsed RF fields can result in acoustic effects – microwave hearing as discussed in Chapter 6, paragraph 5. This is a thermal effect and is only detectable at high peak powers. So there would need to be another mechanism if, for example, biological effects of pulsing occurred at the power levels of TETRA handsets. One possible route could involve demodulation. In modulated RF waves, such as those used in telecommunications, information transmission is achieved by varying the amplitude of the RF (carrier) wave at a relatively low frequency, typically a few kHz or tens of kHz. Demodulation is the process of retrieving this information. If biological tissue were capable of demodulating RF signals, the electric fields inside the tissue would also include components at these low frequencies. For digital transmission, the low frequency component would cover a relatively wide band, 'white noise', and if the carrier wave were pulsed, would also contain components at the pulse frequency and its harmonics. If these low frequency electric fields were large enough they could result in biological effects (eg Saunders and Jefferys, 2002).

21 Demodulation would occur if the electrical conductivity or dielectric constant of a biological component varied significantly with electric field, E, so that its electrical response was non-linear. For example, if its conductivity varied as $aE + bE^2$, there would be components of current at the modulation frequencies that would become significant at fields at which $bE \sim a$. In most dielectrics this requires very large fields approaching those at which dielectric saturation or breakdown occurs and the only known example of a biological component that is non-linear at fields below ICNIRP reference levels is a cell membrane. The neutral lipid bilayer separates regions of opposite polarity so that the charge distribution is similar to that of a semiconductor junction. The non-linear response is, however, only observed at frequencies below about 500 kHz (Montaigne and Pickard, 1984; Kotnik and Miklavčič, 2000) so could not, for example, produce demodulation of the RF waves used in mobile telecommunications. Investigations of the non-linearity of other biological components at these higher frequencies would therefore seem very desirable and a very sensitive technique to do this has recently been proposed by Balzano (2002, 2003a) and Balzano and Sheppard (2003). The proposal has led to correspondence by Adair (2002, 2003b), Balzano (2003b,c), Kaune (2003), Marino (2003) and Marino and Frilot (2003).

22 Further discussion of some of this work on mechanisms is given in several reviews that have appeared since the IEGMP report (Foster and Baish, 2000; Pickard and Moros, 2001; Sheppard et al, 2001; Adair, 2003a).

GENOTOXIC EFFECTS

Mutation studies

23 A rapid method to assess genotoxicity is *in vitro* mutation. Most reports of low intensity RF radiation show no change in the rate of mutation. However, at higher intensities where heating cannot be excluded, rates can be increased (IEGMP, 2000, Sections 5.125–5.144).

24 A study in yeast (Gos et al, 2000) that used exposures to pulse modulated 900 MHz with SARs of 0.13 and 1.3 W kg^{-1} (whether these were peak or mean values was not stated) found no change in the mutation rates due to the RF exposure either alone or in combination with a known genotoxic compound, methyl methansulphonate.

Chromosomal damage

Chromosomal aberrations

25 A variety of agents can cause chromosomal aberrations. These chromosomal rearrangements can be seen using light microscopy and are thought to be indicative of genotoxicity. They can accumulate in non-dividing cells but may be lost in cells undergoing division. The consequence of these aberrations is unclear, but they may be associated with cancer, developmental abnormalities or spontaneous abortion.

26 Several studies have reported significant increases in chromosomal aberrations in a range of isolated cells after diverse exposures, but this is balanced by studies using similar cells and exposures that found no increase. In some of the studies that found positive results the influence of thermal effects could not be excluded (IEGMP, 2000, Section 5.138).

27 In the few more recent studies on chromosomal aberrations in isolated human lymphocytes there were again divergent findings (summarised in Table 3.1, page 64). Maes et al (2001) found no effect using 900 MHz radiation with SARs from 0 to 10 W kg^{-1} in three different modes: continuous, pseudo-random and dummy burst (presumably the SARs quoted for pseudo-random and dummy burst were peak values). Similarly, Vijayalaxmi et al (2001a,b) found no change in peripheral blood cells when exposed for 24 hours to either 835 MHz FDMA or 847 MHz CDMA, with mean SARs up to 5.5 W kg^{-1}, whereas exposure to gamma radiation produced a significant increase in aberrations. In contrast, Mashevich et al (2003), using apparently similar exposure conditions – 830 MHz continuous wave with mean SAR values in the range 1.6–8.8 W kg^{-1}, although for 72 hours – found aneuploidy in chromosome 17 which increased with SAR values. In addition, there was abnormal replication in chromosome 17 of the region dealing with segregation. The main difference between these studies appears to be the exposure time, 24 or 72 hours. It would be of interest to know if the authors who found no effect after 24 hours of RF exposure would have done so after 72 hours. Both 24 and 72 hours of continuous exposure are long times compared with normal mobile phone use and the SAR values are many orders of magnitude greater than would be received from a mobile phone base station. However, if the longer exposure times can be confirmed to have a detrimental effect on isolated cells, it would be essential to know if the exposure period needs to be continuous or whether shorter periods, if additive, could achieve the same result.

Micronucleus formation

28 Micronucleus formation, the occurrence of cells with unusually small nuclei, is thought to be the consequence of breaks in the DNA. The estimation of the frequency of micronucleus formation as a result of chromosomal damage is thought to be quite sensitive as micronucleus formation can accumulate particularly in non-dividing cells. However, micronuclei also occur in normal cells, making the interpretation of experiments more difficult.

29 Increased micronucleus formation has been shown in studies of various isolated cells exposed to RF radiation, but the exposure conditions were generally poorly defined or were sufficiently intense to cause thermal effects (IEGMP, 2000, Section 5.141).

30 Recent studies also show a mixed picture, with no consistent pattern emerging as to what exposure conditions cause increased micronucleus formation (see Table 3.1). No increase was found in isolated human lymphocytes or C3H 10T½ mouse fibroblast cells exposed for up to 24 hours to either 835 MHz FDMA or 847 MHz CDMA radiation, with a mean SAR up to 5.5 W kg^{-1} (Vijayalaxmi et al 2001a,b; Bisht et al, 2002). In a study that found increased formation rates, Tice et al (2002) showed that human lymphocytes exposed for 24 hours to 837 MHz pulsed RF, 837 MHz CDMA or 1909 MHz radiation, with a mean SAR of 5 or 10 W kg^{-1}, were significantly affected by both continuous wave and pulse modulated signals. However, although lymphocytes were sensitive to exposure, human blood leukocytes were not responsive and no effect was seen with these cells. Zotti-Martelli et al (2000) also exposed human lymphocytes, but to 2.45 or 7.7 GHz continuous wave radiation, and showed significant increased formation rates at a power density of 300 W m^{-2} for 30 or 60 minutes. However, SAR values were not quoted and it would be difficult at these power densities to exclude the possibility of

localised heating in the cells despite the experiment being performed in a room at 20 °C. Zhang et al (2002) also exposed human lymphocytes to 2.45 GHz radiation (presumably continuous wave) at a power density of 50 W m^{-2} (no SAR value given) for 2 hours and found no increase in micronuclei. In addition, there was no synergistic genotoxic effect over mitomycin alone.

31 D'Ambrosio et al (2002) found that a phase modulated (without amplitude modulation) 1800 MHz GSM signal produced a significant effect, but a continuous wave signal did not, in human lymphocytes exposed to 1.7 GHz radiation for 15 minutes with a maximum SAR of 5 W kg^{-1}. This might suggest that the phase modulation is necessary for the genotoxic effect, which seems rather improbable.

32 Thus in this small group of studies the results are apparently contradictory and confusing, ranging from no effect of exposure of human lymphocytes to a continuous wave 835 MHz signal, to a positive effect for both continuous and pulse modulation, providing exposure was for 24 hours. Use of a higher frequency, 2.45 GHz, at 300 W m^{-2} for only 60 minutes was sufficient to increase micronuclei, but at 50 W m^{-2} for 2 hours it did not. However, the effect of heating at the higher power levels cannot be excluded. At 1.748 GHz, continuous wave had no effect but phase modulation did cause stimulation. The lack of a consistent pattern of response in the same cell type makes it difficult to interpret the significance of the findings. However, with mean SAR values up to 10 W kg^{-1} in some experiments, the effect of heating could not be excluded.

Sister chromatid exchange

33 Sister chromatid exchange, the switching of DNA from one part of a chromosome to another, is an early marker of genotoxic effects and is believed to be due to the replication of damaged DNA. It is a widely used and accepted test of genotoxicity.

34 Mainly negative results have been reported over a wide range of RF exposures, intensities and cell types, and the one exception (Khalil et al, 1993) may have had a flawed methodology (IEGMP, 2000, Section 5.140).

35 The only recent study, Maes et al (2001), found no indication of sister chromatid exchange in human lymphocytes exposed to continuous wave or pulsed 900 MHz radiation with SARs between 0 and 10 W kg^{-1}.

DNA damage

Comet assay

36 The comet assay or single cell gel electrophoresis assay is a sensitive method for measuring DNA strand breaks in individual cells and is used to assess DNA damage. The damaged DNA migrates during electrophoresis out of the nucleus towards the anode; the resulting comet-like appearance is visualised microscopically by fluorescent staining of the DNA.

37 Studies *in vitro* have not shown direct effects of damage to DNA at power densities up to 100 W m^{-2} and SARs up to 20 W kg^{-1} (IEGMP, 2000, Section 5.130).

38 These negative findings are continued in more recent studies (Table 3.1). Vijayalaxmi et al (2000) exposed isolated human lymphocytes to a 2.45 GHz signal with a mean SAR of 2.1 W kg^{-1} for 2 hours. The comet assay showed no significant difference from the sham exposed controls, in contrast to the cells exposed to ionising radiation. Similarly, mouse fibroblast cells (C3H 10T½) exposed to 847 MHz CDMA or 835 MHz FDMA

radiation with a mean SAR of 3.2–5.1 W kg^{-1} for 2, 4 or 24 hours had no induced damage (Li et al, 2001). Miyakoshi et al (2001) exposed human-brain-tumour-derived MO54 cells for 2 hours to 2.45 GHz radiation with an SAR up to 100 W kg^{-1} and found no DNA damage. Isolated human leukocytes (Tice et al, 2002) also showed no DNA damage when exposed for up to 24 hours to 837 MHz pulsed RF, 837 MHz CDMA or 1909 MHz radiation with mean SARs of 1–10 W kg^{-1}. McNamee et al (2002a,b) similarly found no DNA damage when human leukocytes were exposed to 1.9 GHz radiation (mean SAR 0–10 W kg^{-1}) using either pulse modulated or continuous wave modes. Furthermore they were unable to show any increase in micronuclei at these exposures. Zhang et al (2002) exposed human lymphocytes to 2.45 GHz radiation at a power density of 50 W m^{-2} (no SAR value available) and found no effect of RF radiation alone. However, in combination with the genotoxic agent mitomycin there was a significant increase above that of mitomycin alone. This result was somewhat weakened by the fact that it only occurred in one of the four mitomycin concentrations tested.

39 In general, the studies of genotoxic effects are negative. There was no evidence of direct damage to DNA. There was one new report of chromosomal aberration but none for sister chromatid exchange.

OTHER EFFECTS THAT MIGHT LEAD TO CARCINOGENESIS

Cell transformation

40 Cell transformation is one stage on the multistage path to malignancy and involves the release of cells from contact inhibition. Transformed cells, in contrast to normal cells, continue to proliferate despite the close contact of other cells. Although there is little evidence that RF radiation has a direct carcinogenic effect it may be an epigenetic factor, ie it might act synergistically in combination with known mutagens or promoting agents to enhance their effect.

41 There are several studies suggesting that RF radiation can have an epigenetic effect. However, the evidence is equivocal as there are studies with similar cell types and exposures that show no effects. In some of the studies the effect of heating cannot be excluded and this alone can augment the action of some agents (IEGMP, 2000, Sections 5.148–5.151).

42 In a study of neoplastic transformation, Roti Roti et al (2001) exposed C3H 10T½ mouse fibroblasts to 835 MHz FDMA or 847 MHz CDMA for 7 days with a mean SAR of 0.6 W kg^{-1}. To test for epigenetic effects the RF exposure was also made in combination with 4.5 Gy x-rays. There was no increase in transformation rates due to RF radiation either alone or in conjunction with x-rays.

Ornithine decarboxylase (ODC)

43 Ornithine decarboxylase is a key enzyme required for cells to grow and divide. Its activation is related to cell proliferation and most tumour promoters, although not all, increase the activity of ODC. In this regard ODC activity has been used in cells to test for tumour promoting agents. The effect of RF radiation on ODC is extensively reviewed in the Royal Society of Canada Expert Panel Report (1999) and this was updated by the IEGMP (2000) report. Both concluded that there may be a slight increase in ODC levels but the changes were small compared with chemical promoters, where there can be up

to a 500-fold increase. These small changes were unlikely to have an effect on tumour promotion either alone or in synergy with other agents. There have been no new studies at the time of writing.

Cell proliferation

44 Factors that increase cell proliferation may play a role in carcinogenesis. There have been a number of studies into the influence of RF exposure on this process. The findings are summarised by the Royal Society of Canada Expert Panel Report (1999) and the IEGMP (2000) report. In general, the results have been mixed. There were some modest increases in proliferation, but there were also studies showing no effect or even a decrease.

45 Only a few studies have been undertaken since 2000 (see Table 3.2, page 65). Higashikubo et al (2001) investigated the effect of 835 MHz frequency modulated continuous wave (FMCW) or 847 MHz CDMA at a mean SAR of 0.6 W kg^{-1} for up to 100 hours on C3H 10T½ mouse fibroblasts and U87MG human glioma cells. Five cell cycle parameters were examined, including transit time through G1, G2 and S phase, and the probability of cell division. No cell changes were seen in either mode of RF radiation when compared with the sham exposed.

46 Wang YP et al (2001) studied the effect of exposure on nasopharyngeal carcinoma cells subjected to 42.2 GHz radiation with a power density of 10 W m^{-2} for 30 minutes each day for 4 days. Cell proliferation was inhibited and apoptosis induced. There are no details as to whether this was continuous wave or pulsed RF exposure, and no SAR values were reported.

47 Cell proliferation was also inhibited in three tumour cell lines but not in two healthy cell lines tested in a study by Chidichimo et al (2002). Hence the authors feel that this may have a role in the treatment of cancer cells. The cells were exposed to a sweep of RF frequencies in the range 50–80 GHz at a peak power density of 0.7 mW m^{-2} (no SAR value was given) for 1 hour every other day.

OTHER CHANGES IN CELLULAR PROCESSES

Gene expression

48 Chromosomes contain genes and genes require activation for the production of proteins. The activation of a gene is referred to as gene expression; this expression can be switched on or off. In response to stimulation, genes known as early genes are switched on; the expression of these genes is a sensitive early marker of adaptive cellular changes. The expression of these early genes can be caused by a variety of stimuli, those that have normal cellular functions but also by potentially harmful agents.

49 Particular genes are activated in response to stress experienced by the cell – for example, the genes that produce heat shock proteins. These protective proteins are formed to safeguard the cell and its functions in response not only to heat but also to chemical and physical agents that cause cellular stress.

50 An invertebrate model established to examine the stress-induced gene expression of the heat shock protein gene in the soil nematode *Caenorhabditis elegans* was described by Daniells et al (1998). They used a transgenic strain of nematode that had been modified so that when the gene for heat shock protein was switched on it also

activated an adjoining reporter gene. Two different reporter genes were used: one produced an enzyme β-galactosidase, and the other a green fluorescent protein. Worms exposed for a few hours to continuous wave or pulsed 750 MHz radiation had elevated levels of gene expression. Similar results were obtained with emissions from a conventional mobile phone (IEGMP, 2000, Section 5.118).

51 The same research group (de Pomerai et al, 2000, 2002) has continued its work on the nematode model (Table 3.2). The group has shown that an overnight exposure to 750–1000 MHz radiation, with an estimated SAR of 1 mW kg^{-1}, increased heat shock protein gene expression, growth rate and the proportion of worms maturing into egg-bearing adults. Whether this exposure was continuous wave or pulsed, and if the SAR was peak or mean, was not mentioned. The effect on heat shock protein was equivalent to the result of a 3 °C rise in bulk temperature. Not only was there no observed increase in temperature as the result of RF exposure but also an enforced 3 °C rise caused the opposite effect on growth and maturation to that of RF exposure, implying that the effect of RF radiation on nematodes was not due to bulk heating of the worms.

52 Other studies have also described an increase in the production of heat shock proteins. Kwee et al (2001) exposed transformed human epithelial amnion cells to pulse modulated 960 MHz, with an SAR of 2.1 mW kg^{-1}, for 20 minutes and found increased levels of Hsp-70, but not Hsp-27. This level of SAR, whether it is peak or mean (the authors did not say), is low and therefore the result is unlikely to be explained by a heating artefact. The time scale of 20 minutes is also very short: heat shock proteins when induced by heat normally take a longer time to show increased concentrations in the cell and would normally reach a maximum after approximately 6 hours. In these experiments the increase in Hsp-70 was no longer present after 90 minutes.

53 Tian et al (2002) used a continuous wave 2.45 GHz signal to expose MO54 cells. Hsp-70 expression only increased in mean SARs above 20 W kg^{-1}; it increased further with exposure time. The authors concluded that as the level of expression of Hsp was higher in RF exposed cells than in the raised temperature control (39 °C), the extra Hsp expression was not solely due to the heat. Whether this conclusion is justified would need to be tested. However, there is no doubt that a mean SAR value of 20 W kg^{-1} will cause heating.

54 Leszczynski et al (2002) used human endothelial cells exposed for 1 hour to pulse modulated 900 MHz radiation with a mean SAR of 2 W kg^{-1}. They showed that the pattern of protein phosphorylation changed and there was a transient increase in the expression of Hsp-27 and p38MAPK. However, there was no statistical analysis to support the results presented in the paper. Based on the possible increase in Hsp-27 expression the authors put forward a hypothesis that radiation from mobile phones may:

(a) facilitate the development of brain cancer by inhibiting the cytochrome c/caspase apoptotic pathway,
(b) cause an increase in blood–brain barrier permeability through stabilisation of endothelial cell stress fibres.

55 Although an interesting hypothesis, the study has little to support such a mechanism. There is an unquantified changed in Hsp-27 in a cell culture of endothelial cells that may or may not be biologically significant. The authors have shown neither a subsequent inhibition of cytochrome c nor stabilisation of endothelial stress fibres. This possible increase in Hsp-27 effect, even if significant *in vitro*, has little bearing *in vivo*.

56 Longer-term exposure of chick embryos – for 4 days of 30 or 60 minutes each day – to 915 MHz radiation, with a calculated SAR of 1.7 W kg^{-1}, caused a decline in Hsp-70 in contrast to short exposures that stimulated Hsp-70 expression (Di Carlo et al, 2002). Whether this was a pulsed modulated or continuous wave signal, and whether the SAR was peak or mean, was not included in the paper.

57 Pacini et al (2002) found a wide range of effects in human skin fibroblasts exposed for 1 hour to a pulse modulated 902 MHz signal with a mean SAR of 0.6 W kg^{-1}; these included increased gene expression, inhibition of cell growth, and DNA synthesis.

58 Natarajan et al (2002) investigated the effect of high peak power pulsed RF radiation on nuclear factor kappa B, a protein that binds to DNA and is an important regulator of DNA transcription. Transcription is the process by which an RNA copy is made of the DNA following gene activation. The RNA is subsequently used as a template to synthesise protein. Human monocytes (Mono Mac-6) were exposed to RF radiation at 8.2 GHz pulsed at 1000 Hz with a pulse duration of 2.2 µs. The mean SAR was 10.8 W kg^{-1} for 90 minutes, although 10% of the cells could possibly have been receiving 22–29 W kg^{-1}. There was a 3.6-fold increase in nuclear factor kappa B activity, but because of the broad spectrum of SAR experienced by the cells the authors were not prepared to rule out thermal effects.

Intracellular signalling

59 Cells receive information via external signals and many cell-signalling pathways include a transient increase in intracellular calcium. This increase can be due to release from internal stores or an influx of calcium across the cell membrane from the surrounding fluid. Intracellular calcium concentrations are tightly controlled by the cell and are maintained at a level approximately 1000-fold less than the surrounding fluid. Transient increases in the concentration of calcium in the cell act as a trigger for various other cellular processes. This mechanism is common to many types of cells and hence factors that change the intracellular calcium concentration can have a diverse range of effects depending on the type of cell affected. Much of the early work on RF exposure focused on calcium movement in brain tissue.

Calcium flux

60 The IEGMP report (2000, Section 5.59) concluded that the evidence that RF exposure caused an increase of the rate of calcium release (or efflux) from brain tissue was contradictory. The suggestion that this effect occurred specifically with pulse modulated RF signals was intriguing but the implication for cell function was considered unclear and there was no obvious health effect.

61 A further review of the literature was undertaken (AGNIR, 2001) which examined the evidence for a role of pulse modulated (in particular, 16 Hz modulation) RF fields in causing an increased efflux of calcium from tissue and cells. The report summarised the studies regarding the tissue and cellular studies briefly as follows:

> **'The existence of changes in calcium efflux, and their significance if they occur in living tissue, are much disputed. The design and interpretation of the early studies were not ideal and they were predominantly carried out using non-living tissue. Since the early 1980s a number of generally better designed studies have failed to detect an increase of calcium efflux from**

tissues as a result of RF exposure under a variety of conditions and modulations. If the phenomenon is biologically significant, concomitant changes would be expected in the functions of nervous tissues that depend on the movement of calcium ions, but none has been unambiguously shown to occur.'

62 The advent of sensitive fluorescent dyes specific for calcium has made the technique of real-time estimation of intracellular calcium concentrations in individual cells possible. This is a sensitive indicator of cell pathology and shows transient changes not only within the cell but also in the flux of ions from the cell. Although this technique has been applied to low frequency electromagnetic field exposures, few studies so far have used it in RF experiments.

63 Cranfield et al (2001) exposed human leukaemic T-cells (Jurkat cells) to 915 MHz radiation, with a mean SAR of 1.5 W kg^{-1} for 10 minutes. The intracellular calcium concentration was estimated using a calcium-specific fluorescent dye in individual cells following a blind and randomised sham exposure or exposure to RF radiation. Both continuous and pulse modulated RF (217 Hz) signals were studied. No effect of RF exposure on mean calcium level was detected, nor were there changes in the percentage of cells showing spikes in calcium concentration, spike height or number of spikes. In one combination of experimental conditions there was a significant change in mean frequency of calcium spikes but this was difficult to assess and may have been a statistical anomaly.

64 No change in intracellular calcium concentration was seen in dissociated cerebellar granule cells or neonatal rat myocytes (Green et al, 2002) when exposed for 20 minutes (maximum SAR of 0.4 W kg^{-1}) to RF fields used for TETRA which have a 380 MHz signal pulse modulated at 17.6 Hz.

65 Tattersall et al (2001) used a rat hippocampal slice model to investigate the effect of RF exposure on electrical activity, which will have been sensitive to intracellular calcium concentration. The slices were exposed to continuous wave 700 MHz radiation with a maximum SAR of 4.4 mW kg^{-1} for up to 15 minutes, although there may have been a 25-fold increase in SAR around the stimulating electrodes (Wang Z et al, 2001). Increases up to 120% and decreases of 80% were seen in the excitability of the hippocampal tissue.

Membrane effects

66 The cell membrane is a lipid bilayer that plays an important role in cellular function, from maintaining the correct internal environment to mediating and interpreting external signals.

67 The view of IEGMP (2000, Section 5.52) was that there was evidence that RF radiation could affect membrane proteins and the movement of ions across membranes. However, some of the effects only occurred at below normal body temperatures or with RF intensities that could cause heating.

68 Sajin et al (2000) found a significant increased loss of haemoglobin from human erythrocytes exposed to 2.45 GHz radiation with power densities of 0.25 to 100 W m^{-2} (no SAR values were quoted). However, exposures greater than ten hours with a power density of 50 W m^{-2} appeared to exert a protective effect against spontaneous haemolysis.

69 An *in vitro* model of the blood–brain barrier using rat astrocytes and porcine brain capillary endothelial cells was investigated by Schirmacher et al (2000). The model was exposed to 1.8 GHz radiation modulated at 217 Hz, with a mean SAR of 0.3 W kg^{-1}, and monitored over four days. The permeability to sucrose was significantly increased compared with non-exposed controls.

Direct effect on proteins

Enzyme activity

70 Enzymes are proteins that catalyse chemical reactions; each enzyme is specific to a particular reaction and hence there are hundreds of different types of enzymes in the body. They play a vital role in function both within cells and in the body fluids, their activity being regulated by various local factors.

71 Pashovkina and Akoev (2000, 2001) investigated the effects of 2.4 GHz radiation pulse or amplitude modulated at 10–390 Hz with power densities up to 80 mW m^{-2}. They showed that RF radiation for one to three minutes with an amplitude modulation frequency of 70 Hz caused a two-fold increase in guinea pig serum alkaline phosphatase. Furthermore the aspartataminotranspherase activity of donor blood was dependent on both the pulse modulation and intensity. The maximum effect, a six-fold increase, occurred after five minutes at 390 MHz and 80 mW m^{-2}. No SAR values were given.

72 A power density 1000-fold higher was required to affect the activity of acetylcholinesterase in frog skeletal muscle (Ivanov et al, 2001). An exposure of continuous wave 2.45 GHz radiation at 100 W m^{-2} for 30 minutes caused a 26% decrease in enzyme activity. No SAR value was given for this power density; it is therefore possible that there was a heating effect. The effect of pulse modulation was not investigated in this study.

73 Safronova et al (2002) exposed mouse neutrophil cells, primed by a low dose of chemotactic agent, to 41.95 GHz radiation with an SAR of 0.45 W kg^{-1} to show enhanced activation of the cells when triggered by a higher dose of the agent. The study indicated that protein kinases, key cellular enzymes that phosphorylate proteins, were actively involved in the process.

74 An ultra-wide band pulsed signal was used to expose macrophages (RAW 264.7 cells). The cells received 1 ns pulses repeated at 600 Hz with an estimated average SAR of 0.106 W kg^{-1} for 30 minutes (Seaman et al, 2002). Nitric oxide production was unchanged unless nitrate was added to the culture medium, indicating a possible induction of nitric oxide synthase by ultra-wide band pulses.

SUMMARY

75 Since the IEGMP report was published in 2000, a number of possible mechanisms for interaction between RF radiation and biological tissue have been explored theoretically. Attention has been given to the possibility that RF radiation can produce changes in protein conformation. For RF fields below guideline values, it has been shown that these cannot occur as a result of transient changes in temperature. An alternative model has been given involving RF excitation of coupled states of different conformation but no estimates have been made of the fields required to produce

detectable effects. Ion pumping across membranes can evidently occur for RF fields above guideline values at frequencies below a few MHz and has been qualitatively accounted for by a theory involving changes in protein conformation. The effects have not so far been explained quantitatively but seem unlikely to occur at higher frequencies. The assumptions of the Fröhlich model seem to be increasingly improbable following calculations of the lifetimes of vibrational states in structures such as microtubules and also of the very small energies that can be stored in these states as a result of exposure to RF radiation.

76 There have also been suggestions that biological effects might arise either through the excitation of plasma-like excitations at the surface of cell membranes or through changes in the probability of ligand binding to cell receptor proteins, but no reliable estimates have been made yet of the size of RF fields required to produce them. Experimental work on bacteria containing magnetite found no effects attributable to RF exposure. The work leaves open the question as to whether the low frequency fields from handsets can interact sufficiently with the magnetite to produce bioeffects. The possibility that chemical reactions can be influenced by RF exposure through the radical pair mechanism, and that this could have biological implications, is worth further investigation.

77 There has been very little discussion of non-linear mechanisms through which biological components might demodulate RF signals. However, a detailed proposal has been advanced to investigate non-linearity experimentally at the frequencies used for mobile telecommunications and the technique would appear to be capable of great sensitivity. Strong non-linearity at frequencies above 1 MHz seems unlikely but, if present, would result in electrical signals at pulse frequencies.

78 There is no overall convincing evidence to support the view that RF radiation is directly carcinogenic or that it promotes other carcinogenic agents. The studies are summarised in Table 3.1. Most of the criteria used to assess genotoxicity are negative. There was no increase in cell proliferation, cell transformation, mutation rate or sister chromatid exchange. Only one study found a chromosomal aberration and another reported that there was DNA damage through synergy with a genotoxic agent, although only at one dose. The results from the micronucleus assays are variable. For instance, in one laboratory human lymphocytes exposed to 837 MHz radiation, with an SAR of 5 or 10 W kg^{-1}, for 24 hours showed an increased incidence of micronuclei; in another, human lymphocytes exposed to 835 MHz radiation, with an SAR of 5.5 W kg^{-1}, for 24 hours showed no increase, ie apparently similar conditions produced contrasting results. The importance to human health of the occurrence of micronuclei in isolated cells is unclear. This difficulty in interpretation is compounded by there being a natural incidence of micronuclei in normal cells.

79 In the recent papers reviewed (summarised in Table 3.2) there appears to be some evidence for an increase in expression of heat shock proteins in response to RF exposure. However, the exposure conditions and timings needed to evoke this response vary between the models. At the higher SAR values the effects of heating may play a contributory factor; at the lower SAR values (1 mW kg^{-1}) this would seem unlikely to be the case. The results reviewed in these few studies are too inconsistent to draw any conclusions. For instance, the pattern of which heat shock protein increased, Hsp-27 or Hsp-70, varied between the models. The fact that all the studies

TABLE 3.1 *Possible carcinogenic effects*

Cell type	Exposure	Results	Reference
Human leukocytes	1.9 GHz CW or 6.7 ms pulse at 50 pps for 2 h, SAR 0–10 W kg^{-1}	No DNA damage. No increase in micronuclei formation	McNamee et al, 2002a,b
Human leukocytes Human lymphocytes	837 MHz CDMA, 837 MHz TDMA, 1.9 GHz for 3 or 24 h, SAR 1–10 W kg^{-1}	4-fold increase in micronucleus induction in lymphocytes. No effect on leukocytes	Tice et al, 2002
Human lymphocytes	1.7 GHz for 15 min, max SAR 5 W kg^{-1}	Increase in micronucleus induction in phase modulated field	d'Ambrosio et al, 2002
Human lymphocytes	900 MHz CW or pulsed (GSM), 0.58 ms pulses at 217 pps for 2 h, SAR 0–10 W kg^{-1}	No increase in chromatid aberrations or sister chromatid exchange	Maes et al, 2001
Human lymphocytes	CW 830 MHz for 72 h, mean SAR 1.6–8.8 W kg^{-1}	Aneuploidy of chromosome 17, abnormal replication of region dealing with segregation	Mashevich et al, 2003
Human lymphocytes	2.45 GHz, 7.7 GHz for 30–60 min, 300 W m^{-2} (no SAR)	Up to 5-fold increase in micronucleus induction	Zotti-Martelli et al, 2000
Human lymphocytes	2.45 GHz for 2 h, 50 W m^{-2} (no SAR)	No increase in micronucleus induction. Synergistic genotoxic effect at one dose of mitomycin	Zhang et al, 2002
Human lymphocytes Mouse fibroblasts C3H 10T ½	836 MHz FDMA for 24 h, SAR 5.0 W kg^{-1} 848 MHz CDMA for 24 h, SAR 5.5 W kg^{-1} 2.45 GHz for 2 h, SAR 2.1 W kg^{-1}	No increase in chromosomal aberrations, micronuclei induction or DNA damage	Vijayalaxmi et al, 2000, 2001a,b
Mouse fibroblasts C3H 10T ½	836 MHz FDMA for 3–24 h, SAR 5.1 W kg^{-1} 848 MHz CDMA for 3–24 h, SAR 4.8 W kg^{-1}	No increased micronuclei induction	Bisht et al, 2002
Mouse fibroblasts C3H 10T ½	836 MHz FDMA, 848 MHz CDMA for 24 h, SAR 3.2–5.1 W kg^{-1}	No DNA damage	Li et al, 2001
Mouse fibroblasts C3H 10T ½	836 MHz FDMA, 848 MHz CDMA for 7 d, mean SAR 0.6 W kg^{-1}	No change in transformation frequency	Roti Roti et al, 2001
Mouse fibroblasts C3H 10T ½ Human glioma U87MG	836 MHz FMCW, 848 MHz CDMA for 100 h, mean SAR 0.6 W kg^{-1}	No change in cell progression	Higashikubo et al, 2001
Brain tumour MO54 cells	2.45 GHz for 2 h, SAR 100 W kg^{-1}	No DNA damage	Miyakoshi et al, 2001
Nasopharyngeal carcinoma CNE	42.2 GHz for 30 min per day, 4 days, 10 W m^{-2} (no SAR)	Cell proliferation inhibited	Wang YP et al, 2001
MCF7, K562, epithelial cells	54–78 GHz for 1 h per day, 0.7 m W m^{-2} (no SAR)	Cell growth inhibited	Chidichimo et al, 2002
Yeast *saccharomyces cerevisiae*	900 MHz pulsed (GSM), 0.58 ms pulses at 217 pps for 36 h, SARs 0.13 and 1.3 W kg^{-1}	No increase in mutation rate	Gos et al, 2000

CW = continuous wave
CDMA = code division multiple access
FDMA = frequency division multiple access
FMCW = frequency modulated continuous wave
GSM = global systems for mobile telecommunications
TDMA = time division multiple access

TABLE 3.2 *Changes in cellular processes*

Cell type	Exposure	Results	Reference
Nematode *C elegans*	0.7–1 GHz for 20 h, SAR 1 mW kg^{-1}	Growth rate increased 11% Maturation to adulthood increased 40%	de Pomerai et al, 2002
Human epithelial amion	960 MHz pulsed (GSM), 0.58 ms pulses at 217 pps for 20 min, SAR 2.1 m W kg^{-1}	Increased heat shock protein Hsp-70, Hsp-27 could not be detected	Kwee et al, 2001
Chick embryo	915 MHz for 1 h per day, 4 days, SAR 1.7 W kg^{-1}	Decreased protection against hypoxia	Di Carlo et al, 2001
Human glioma MO54	2.45 GHz CW for 2–16 h, SAR 5–100 W kg^{-1}	SAR above 20 W kg^{-1}, 2 h increased Hsp-70	Tian et al, 2002
Human endothelial EA.hy926	900 MHz pulsed (GSM), 0.58 pulses at 217 pps, mean SAR 2 W kg^{-1}	Transient increase in Hsp-27 phosphorylation	Leszczynski et al, 2002
Human skin fibroblasts	902 MHz pulsed (GSM), 0.58 ms pulses at 217 pps, mean SAR 0.6 W kg^{-1}	Increased gene expression and DNA synthesis	Pacini et al, 2002
Human monocytes	8.2 GHz, pulsed, 2.2 μs pulse at 1000 pps for 90 min, mean SAR 11 W kg^{-1}	3.6-fold increase in binding activity of NF-kappa B	Natarajan et al, 2002
Mouse neutrophils	41.95 GHz, SAR 0.45 W kg^{-1}	Enhanced activation response to chemotactic agent	Safronova et al, 2002
Human leukaemic T-cells	915 MHz CW or pulsed (GSM), 0.58 ms pulses at 217 pps for 10 min, SAR 1.5 W kg^{-1}	No change in calcium level or signalling	Cranfield et al, 2001
Cerebellar granule cells Neonatal rat myocytes	380 MHz pulsed (TETRA), 14.2 ms pulse at 17.6 pps for 20 min, SAR 0.4 W kg^{-1}	No change in intracellular calcium	Green et al, 2002
Rat hippocampal slices	700 MHz CW for 15 min, SAR 4.4 m W kg^{-1}	Changes in electrically evoked field potential (–80 to + 120%)	Tattersall et al, 2001
Human erythrocytes	2.45 GHz for 60 h, 0.25–100 W m^{-1}, 60 h (no SAR)	Biphasic effect on haemolysis, increased by short low power exposures, decreased by higher and longer treatments	Sajin et al, 2000
Rat astrocytes Porcine endothelial	1.8 GHz pulsed (GSM), 0.58 ms pulses at 217 pps for 4 d, mean SAR 0.3 W kg^{-1}	2-fold increase in permeability	Schirmacher et al, 2000
Serum enzymes	2.4 GHz CW or pulse modulation, 50–390 pps for up to 5 min, 80 mW m^{-2} (no SAR)	Alkaline phosphatase activity increased 2-fold; aspartataminotranspherase activity increased 6-fold	Paskovkina et al, 2001a,b
Frog muscle extract	2.45 GHz CW for 30 min, 100 W m^{-2} (no SAR)	Decrease (26%) in acethylcholinesterase activity	Ivanov et al, 2001
Macrophage RAW 264.7	Ultra-wide band for 30 min, SAR 0.1 W kg^{-1}	Increased nitric oxide production	Seaman et al, 2002

CW = continuous wave
GSM = global systems for mobile telecommunications
TETRA = terrestrial trunked radio

reviewed showed positive effects, albeit in different heat shock proteins, over a wide range of exposures is interesting. This may reflect a selection bias toward positive studies in the literature, it could be a heating artefact, or it may be a real phenomenon, which would require confirmatory studies.

80 In contrast to earlier work, studies since the 1980s have generally found no increase of calcium movement in tissues as a result of RF exposure under a variety of conditions and modulations. Two recent studies measured intracellular calcium ion concentration in cells exposed to pulse modulated RF signals. This is a sensitive indicator of cell pathology and shows transient changes not only within the cell but also in the flux of ions from the cell (efflux). These well-conducted studies found no effect of RF modulation on calcium ion concentration, and add further to the doubt about the existence of a specific pulse modulation effect on calcium movement in tissues. At present there are too few well-conducted studies using modern techniques to draw firm conclusions, but the weight of evidence appears to be against there being an effect of pulsed RF radiation on intracellular calcium concentration or flux.

81 The general hypothesis that low frequency pulse modulation of the RF signal is necessary for a biological effect has been neither confirmed nor negated, based on the papers reviewed. Effects, such as micronucleus formation, or lack of effects have been found for continuous wave and a range of pulse modulation frequencies.

82 The results from a four-day exposure of an *in vitro* model of the blood–brain barrier permeability to sucrose are intriguing but would need to be confirmed in animal studies to show that the response also occurred *in vivo*.

83 Although there has been a wide range of diverse exposures and biological models investigated, no consistent pattern has emerged from the cellular studies of RF exposure. The balance of the findings on carcinogenesis is that there is little evidence and no known mechanism to support a direct or indirect effect of RF radiation on this process. Positive findings are not confirmed by other independent studies; apparently similar experiments fail to confirm each other and may even show contradictory results.

84 The IEGMP report (2000) concluded that: the radiation lacks sufficient energy to disrupt molecular bonds directly; the literature on non-thermal effects is inconsistent; the effects reported are typically small and close to the level of statistical noise. A review of the more recent literature confirms that these conclusions are still valid for the experimental cellular studies.

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4 Animal Studies

1 Attention has been particularly focused on the possibility that exposure to radiofrequency (RF) radiation at levels too low to cause significant heating may nevertheless increase the risk of cancer, adversely affect reproduction and development, or impair brain function. These and other possibilities were assessed by IEGMP (2000). Other recent reviews of the literature include those by an Expert Panel of the Royal Society of Canada (1999), AGNIR (2001), Krewski et al (2001a,b) and Zmirou (2001). In this chapter, emphasis is placed on studies published after the IEGMP report.

EFFECTS ON CANCER

2 The possibility that low level exposure to RF fields may increase the risk of cancer is a major concern and one that has received much attention. Laboratory studies have addressed this possibility using well-established animal models. The literature on this topic has been extensively reviewed by a European Commission Expert Group (1996), Juutilainen and de Seze (1998), Brusick et al (1998), Repacholi (1998), Verschaeve and Maes (1998), Moulder et al (1999) and Krewski et al (2001a,b).

Genotoxicity and mutagenesis

3 A number of studies have looked for genotoxic effects in the cells of rodents exposed to RF radiation. Generally, previous reviews of the scientific literature have concluded that the evidence that RF radiation is genotoxic is not compelling (eg Brusick et al, 1998; IEGMP, 2000; Krewski et al, 2001a); many studies were negative, and positive studies were often not corroborated by experiments conducted at other laboratories. Two more recent studies support this view. Vijayalaxmi et al (2001) reported that the incidence of micronuclei* in immature (polychromatic) erythrocytes taken from peripheral blood and bone marrow cells of rats was unaffected by exposure for 24 hours to 2.45 GHz radiation at a whole-body specific (energy) absorption rate (SAR) of 12 W kg^{-1}. A similar study (Vijayalaxmi et al, 2003) found a lack of effect of head-only exposures to pulsed 1.6 GHz RF radiation (typical of the signals used by the Iridium satellite phone system) for 2 years at brain SARs of 0.16 or 1.6 W kg^{-1}.

4 A number of past studies with rodents have indicated that RF exposure does not increase mutation rates in somatic or germ cells when temperatures are maintained within physiological limits (IEGMP, 2000). Subsequent to the IEGMP review, Sykes et al (2001) reported a significant reduction in intrachromosomal recombination events in the splenic tissue of transgenic pKZ1 mice exposed to 900 MHz pulsed radiation. Intrachromosomal recombination is associated with chromosomal deletions and inversions; the pKZ1 transgenic mouse is specifically sensitised to such mutations through the incorporation into the mouse genome of a number of reporter (*lacZ*) genes inverted with respect to a promoter–enhancer construct. The mice were exposed for 30 minutes each day for 1, 5 or 25 days at whole-body SARs of 4 W kg^{-1}. However, the

* Chromosome fragments that, in this case, have not been ejected from the erythrocyte.

data were variable, and the biological significance of a reduction in inversion frequency in the exposed group was not clear. The authors suggested repeating the experiment using larger numbers of animals.

5 More recently, the mutagenic potential of exposure to RF radiation emitted by the Japanese Personal Digital Cellular (PDC) phone system was investigated using the Big Blue™ mice *in vivo* mutagenesis assay (Takahashi et al, 2002). These transgenic mice incorporate multiple copies of bacterial *lac*I genes in their genome, which in this experiment were recovered from brain tissue following RF exposure and examined for mutation frequency using a standard bacterial mutation assay. The mice were exposed or sham exposed for 90 minutes each day, 4 days per week for 4 weeks to pulsed 1.5 GHz RF radiation at SARs in the head of 0.67 or 2.0 W kg^{-1}. The authors found that the DNA mutation frequency in the brain tissue extracted from exposed mice was similar to that in tissue from mice that were sham exposed.

6 These studies are summarised in Table 4.1.

TABLE 4.1 *Genotoxicity and mutagenesis*

Model	Exposure conditions	Results	Reference
Micronucleus formation in rat peripheral blood and bone marrow cells	2.45 GHz CW for 24 h at a whole-body SAR of 12 W kg^{-1}	No effect	Vijayalaxmi et al, 2001
Micronucleus formation in rat peripheral blood and bone marrow cells	1.6 GHz pulsed Iridium satellite phone signals; 9.2 ms pulses at 11 pps whole-body weaning then head only for 2 h per day, 5 days per week for 2 years at brain SARs of 0.16 or 1.6 W kg^{-1}	No effect	Vijayalaxmi et al, 2003
Somatic intra-chromosomal recombination in pKZ1 transgenic mice	900 MHz pulsed GSM; 0.6 ms pulses, 217 pps for 30 min per day for 1, 5 or 25 days at a whole-body SAR of 4 W kg^{-1}	No significant effects on 1-day and 5-day groups, significant reduction in spontaneous mutation frequency for 25-day group	Sykes et al, 2001
DNA mutation frequency in Big Blue™ transgenic mice	1.5 GHz pulsed PDC; 6.7 ms pulses at 50 pps for 90 min per day, 5 days per week for 4 weeks at brain SARs of 0.67 or 2 W kg^{-1}	Deletion mutations slightly increased in both groups but not significantly so. No other differences	Takahashi et al, 2002

Cancer studies

7 Early studies exploring the possibility that RF fields might affect spontaneous tumour incidence tended to suffer from insufficient dosimetry, poor histopathology or inadequate follow-up; more recent studies focusing particularly on the possible effects of RF radiation characteristic of mobile phone transmissions generally reported a lack of effect on tumour incidence using a variety of standard rodent models of cancer (IEGMP, 2000).

8 One particular study (reviewed by IEGMP, 2000), however, reported a significant increase in the incidence of lymphomas in about 100 heterozygous Eμ-*Pim1* female mice exposed to pulsed 900 MHz GSM radiation (Repacholi et al, 1997). These transgenic animals, which are predisposed to be susceptible to lymphoblastic lymphomas, were exposed or sham exposed twice each day for 30 minutes, from soon after birth

until about 18 months old. The SARs were variable and ranged from about 0.008 to 4 W kg^{-1} depending on the age and/or size of the animals. The authors reported that the incidence of all lymphomas (lymphoblastic and non-lymphoblastic) in the exposed mice was almost double that in those sham exposed. However, lymphoma incidence was increasing rapidly in both exposed and sham exposed groups at the time when the study was terminated; in addition, only moribund animals were examined histopathologically (IEGMP, 2000).

9 More recently, an attempt to replicate the above study using larger numbers of animals with improved dosimetry, a longer follow-up period (24 months) and complete histopathology on all animals, did not confirm these results (Utteridge et al, 2002, 2003). Exposure to pulse modulated 898.4 MHz GSM radiation was not associated with any field-dependent increase in lymphoma incidence in mice exposed at whole-body SARs of 0.25, 1.0, 2.0 or 4 W kg^{-1} compared with those sham exposed. However, the study size (120 transgenic mice per group) was too small to detect a low or moderately raised risk.

10 A lack of effect of life-time (78 week) exposure to mobile-phone-type RF transmission frequencies on the incidence of lymphoma induced in mice by exposure to ionising radiation has been reported by Heikkinen et al (2001). In this study, CBA/S mice treated by exposure to a total of 4 Gy x-radiation, which induced a high incidence of lymphomas and, to a lesser extent, other tumours, were subsequently exposed or sham exposed either to Nordic Mobile Telephones (NMT) frequency modulated 902.7 MHz radiation at an averaged, whole-body SAR of 1.5 W kg^{-1} or to pulsed 902.4 MHz GSM radiation at 0.35 W kg^{-1}. Full histopathology was carried out. In neither case did RF exposure affect the incidence of lymphoma or of most other neoplasms. In a few cases, neoplastic changes, such as benign pheochromocytomas, were significantly reduced, and non-neoplastic changes, such as cellular hypertrophy in the pancreas, were increased, but these may have been the chance result of multiple comparisons.

11 The effect of prolonged exposure to mobile-phone-type RF radiation on the incidence of chemically induced brain tumours in rats has been investigated in three separate studies. The first, by Adey et al (1999), has been reviewed by IEGMP (2000) who noted that exposure over a 24-month period to 836.55 MHz radiation with a North American Digital Cellular (NADC) modulation had a slight inhibitory effect on both spontaneous and chemically induced brain tumour incidence. These effects were most noticeable in rats that died before the before the end of the experiment; survival itself, however, was unaffected. The SAR levels were reported to simulate the localised peak brain exposures experienced by mobile phone users. In contrast, a subsequent study of a similar design by the same authors (Adey et al, 2000) reported that exposure to frequency modulated 836.55 MHz radiation of the type used in analogue phones did not affect survival or the incidence of either spontaneous or chemically induced brain tumours. Similarly, Zook and Simmens (2001) found that exposure of rats over a two-year period to continuous or pulsed 860 MHz RF radiation at SARs averaged over the brain of around 1 W kg^{-1} had no effect on the induction of spontaneous or chemically induced brain tumours.

12 La Regina et al (2003) found no effect on survival or the incidence of any spontaneous tumour in rats exposed for two years to pulsed 835 MHz (frequency division multiple access, FDMA) RF or pulsed 847 MHz (code division multiple access,

CDMA) RF radiation. The authors particularly noted that no increases were seen in the incidence of mononuclear cell leukaemia, to which these rats are prone, nor in that of tumours of the central nervous system (CNS) such as gliomas or astrocytomas. However, the experiment will have been relatively insensitive to the latter, since CNS tumours occurred at a low incidence in the sham exposed group (around 1%).

13 The standard medium-term rat liver tumour promotion model, in which neoplastic foci are induced in the liver by diethylnitrosamine and partial hepatectomy, has been used in two studies to examine the potential carcinogenicity of RF radiation emitted by the Japanese Personal Digital Cellular (PDC) phone system (IEGMP, 2000). Briefly, no promoting effect of exposure was found following exposure for six weeks to 1.439 GHz at a whole-body average SAR of 0.45–0.68 W kg^{-1} (Imaida et al, 1998a) or 929.2 MHz at an average SAR of 0.6–0.8 W kg^{-1} (Imaida et al, 1998b). In both studies, morning blood samples taken at the termination of the experiment revealed significantly increased levels of melatonin, corticosterone and adrenocorticotrophic hormone in the exposed animals; in addition, the numbers of neoplastic foci were slightly reduced in both groups, although this was statistically significant only in one study (Imaida et al, 1998a). A later study (Imaida et al, 2000) reported a slight decrease in the neoplastic foci using the same rat liver tumour promotion model, but with melatonin added to the night-time drinking water. This suggested that the electromagnetic field exposure in the two previous studies inhibited the formation of neoplastic foci by increasing levels of circulating melatonin. However, the marginal effects and the concomitant changes in other, stress-related hormone levels, precluded any definite conclusions.

14 Bartsch et al (2002) carried out three replicate experiments looking at the effect of a three-year exposure to a GSM-like pulsed 900 MHz radiation on chemically induced mammary tumours in female Sprague-Dawley rats. The RF exposure was at an average whole-body SAR of 17.5–70 mW kg^{-1}. Overall, there was no statistically significant effect of the RF field on tumour incidence or latency; however, tumour development did differ significantly between the three replicate studies. In particular, the median malignant tumour latency was significantly longer in the exposed animals compared with those sham exposed in the first experiment, but there was no difference between these groups in the two subsequent experiments. A lack of significant effect of GSM-like pulsed RF radiation on the incidence of chemically induced mammary tumours has also been reported by Anane et al (2003); the numbers of animals per treatment group were, however, rather small, and the results were variable.

15 The effect of exposure to pulsed 1.5 GHz RF radiation used in the Japanese Personal Digital Cellular (PDC) phone system on chemically induced skin tumorigenesis was investigated by Imaida et al (2001). Female ICR mice, treated with a single application of the carcinogen DMBA (7,12-dimethylbenz[a]anthracene), were exposed or sham exposed for 90 minutes each day, 5 days per week for 19 weeks; the local SAR in the skin was 2.0 W kg^{-1} but the whole-body average SAR was only 84 mW kg^{-1}. In contrast to a positive control group treated with the chemical promoter TPA (12-O-tetra-decanoylphorbol-13-acetate), no papillomas or carcinomas were seen in the exposed or sham exposed animals.

16 More recently, Heikkinen et al (2003) found that daily exposure to pulsed 849 MHz RF radiation characteristic of Digital Advanced Mobile Phone Systems (DAMPS) or to pulsed 902 MHz GSM RF radiation over a two-year period had no effect on survival or

the incidence of ultraviolet radiation (UVR) induced skin tumours in normal and transgenic mice. The transgenic (K2) mice, which overexpress the human ornithine decarboxylase (ODC) gene, are known to be more sensitive to chemical tumour promotion than their normal counterparts.

17 Other authors have examined the possible effects of RF radiation used in various applications, including some being developed for military use, on spontaneous and induced cancers using rodent models. Jauchem et al (2001), for example, exposed C3H/HeJ mice, which are prone to mammary tumours, to pulsed ultra-wide band (UWB) electromagnetic radiation (which includes RF) for 2 minutes per week for 12 weeks. The animals were observed for a further 64 weeks. No effect was seen on the incidence of mammary tumours or other spontaneous tumours. Similar results had been noted previously in similar experiments using the same mouse strain in which exposure was to pulsed 435 MHz (Toler et al, 1997) and 2.45 GHz radiation (Frei et al, 1998a,b). In addition, Mason et al (2001) found no effect of 94 GHz (millimetre wavelength, or MMW) radiation, which is absorbed mostly in the skin, on the development of DMBA-initiated skin cancers in SENCAR mice. The mice were exposed either once for 10 s to MMW radiation at 10 kW m^{-2}, which was sufficient to heat the skin by 13–15 °C, or twice a week for 12 weeks to MMW radiation at 3.33 kW m^{-2}, sufficient to raise skin temperature by 3–4 °C. Exposure had no effect either as a possible promoter of chemically initiated skin papillomas or as a possible co-promoter (in conjunction with TPA) of such tumours.

18 Cancer studies in animals are summarised in Table 4.2.

Summary

19 Two recent studies using established animal models have found no evidence of genotoxic or mutagenic effects of RF radiation; one of these used radiation characteristic of one type of mobile phone system. Another study reported a significant reduction in intrachromosomal recombination frequency after exposure to GSM-type RF radiation, but the data were variable and the biological significance of this effect is unclear.

20 Recent studies that have examined the carcinogenic potential of mobile phone radiation have generally reported a lack of effect on tumour incidence. Most noteworthy is the study by Utteridge et al (2002), the results of which did not corroborate an earlier study (Repacholi et al, 1997) reporting that exposure to GSM-type radiation caused an increase in lymphoma incidence in a transgenic mouse strain predisposed to lymphoma induction. The later study used a larger number of animals with improved dosimetry, a longer follow-up period and complete histopathology. In addition, exposure to radiation characteristic of various types of mobile phone systems did not affect survival and spontaneous tumour incidence, the incidence of x-ray induced lymphomas, spontaneous and chemically induced brain tumours, or carcinogen-induced mammary tumours and skin tumours in a number of long- and medium-term rodent studies.

21 Two studies relevant to the military use of RF radiation reported a lack of effect of ultra-wide band radiation on mammary tumour incidence in a mouse strain predisposed to their development, and a lack of effect of brief but strongly thermogenic levels of 94 GHz radiation on the incidence of chemically induced skin tumours in mice.

TABLE 4.2 *Cancer studies*

Model	Exposure conditions	Results	Reference
Lymphoma-prone Eμ-*Pim1* transgenic mice	900 MHz pulsed GSM; 600 μs pulses, 217 pps; at whole-body SAR 0.008-4.2 W kg^{-1} for 1 h per day, 7 days per week for 18 months	2-fold increase in lymphoma incidence	Repacholi et al, 1997
Lymphoma-prone Eμ-*Pim1* transgenic mice	898.4 MHz pulsed GSM; at whole-body SARs of 0.25, 1.0, 2.0 and 4.0 W kg^{-1} for 1 h per day, 5 days per week for 104 weeks	No effect on survival or lymphoma incidence	Utteridge et al, 2002
Lymphoma incidence in CBA/S mice exposed to 4 Gy ionising radiation	902.7 MHz NMT analogue signal at a whole-body SAR of 1.5 W kg^{-1} or 902.4 MHz pulsed GSM; 217 pps, at a whole-body SAR of 0.35 W kg^{-1} for 1.5 h per day, 5 days a week for 78 weeks	No effect on survival or incidence of lymphoma	Heikkinen et al, 2001
Spontaneous and chemically induced CNS tumours in Fischer rats	836.55 MHz NADC pulsed; 6.7 ms pulses at 50 pps; brain SAR 0.3–0.5 W kg^{-1}; perinatally and for 24 months	Fewer CNS tumours in exposed group	Adey et al, 1999
Spontaneous and chemically induced CNS tumours in Fischer rats	836.55 MHz FM; brain SAR of 1.0–1.2 W kg^{-1} perinatally and for 24 months	No effect on survival or the incidence of any type of brain tumour	Adey et al, 2000
Spontaneous and chemically induced CNS tumours in Fischer rats	860 MHz CW or 860 MHz pulsed, 15 ms pulses at 11.1 pps; brain SAR 1.0 W kg^{-1} for 6 h per day 5 days a week up to 24 months	No effect	Zook and Simmons, 2001
Survival, spontaneous tumour incidence and hyperplasia in male and femal F344 rats	835 MHz pulsed FDMA or 847 MHz pulsed CDMA RF at a time-averaged brain SAR of 1.3 W kg^{-1} for 4 h per day, 5 days per week for 2 years	No effect on survival, spontaneous tumour incidence or hyperplasia	La Regina et al, 2003
Medium term rat liver tumour promotion model	1.439 GHz pulsed PDC; 6.7 ms pulses at 50 pps, whole-body SAR 0.4– 0.7 W kg^{-1} for 90 min per day, 5 days per week for 6 weeks	No effect	Imaida et al, 1998a
Medium term rat liver tumour promotion model	929.2 MHz pulsed PDC; 6.7 ms pulses at 50 pps; whole-body SAR 0.6–0.8 W kg^{-1} for 90 min per day, 5 days per week for 6 weeks	No effect	Imaida et al, 1998b
Mouse skin carcinogenesis model	1.49 GHz pulsed PDC; 6.7 ms pulses at 50 pps; skin SAR 2.0 W kg^{-1} for 90 min per day, 5 days per week for 19 weeks	No effect	Imaida et al, 2001
UVR-induced skin tumours in transgenic (K2) and non-transgenic mice	849 MHz pulsed DAMPS; 6.67 ms pulses at 50 pps; 902 MHz pulsed GSM; 577 μs pulses at 217 pps; whole-body SAR 0.5 W kg^{-1} for 1.5 h per day, 5 days per week for 52 weeks	No significant effect on survival or skin tumour incidence	Heikkinen et al, 2003
Chemically induced mammary tumours in Sprague-Dawley rats	900 MHz pulsed GSM; 577 μs pulses at 217 pps; whole-body SAR 17.5–70 mW kg^{-1} until sacrifice (< 350 days)	No significant differences on tumour latency or incidence overall	Bartsch et al, 2002
Chemically-induced mammary tumours in Sprague-Dawley rats	900 MHz pulsed GSM; 577 μs pulses at 217 pps; whole-body SAR 0.1–3.5 W kg^{-1} for 2 h per day, 5 days per week for 9 weeks	Variable results but no statistically significant effects	Anane et al, 2003
Mammary tumour-prone mice	UWB pulsed radiation; 1.9 ns pulses at 1 kHz; whole-body SAR 0.01 W kg^{-1} for 2 min per week for 12 weeks	No effect	Jauchem et al, 2001
Mouse skin carcinogenesis model	94 GHz CW for at 10 kW m^{-2} for 10 s, sufficient to raise skin temperature by 3–4 °C, either once only, or twice per week for 12 weeks	No effect	Mason et al, 2001

REPRODUCTION AND DEVELOPMENT

22 The possibility that RF fields may affect fertility, reproduction, and development has been much investigated. These possibilities have been reviewed by Jensh (1997), Verschaeve and Maes (1998) and O'Connor (1999), and most recently considered by IEGMP (2000) and Krewski et al (2001a). Overall, there has been no convincing evidence that exposure to low level RF fields can affect reproduction and development in mammals; where consistent effects have been reported they can be attributed to the thermal insult induced by RF exposure (IEGMP, 2000).

23 Male fertility has long been recognised as susceptible to heat, and animal studies have confirmed a similar susceptibility to RF exposure at thermally significant levels; chronic exposure at non-thermal levels has generally been without effect. Akdağ et al (1999) reported that the epididymal sperm count decreased and the percentage of abnormal sperm increased in rats chronically exposed to 9.45 GHz at a whole-body SAR of about 2 W kg^{-1}. The same authors (Daşdağ et al, 1999) reported that only the seminiferous tubule diameter in rat testes was decreased after only brief daily exposure for a month to mobile phone radiation from commercially available GSM (890–915 MHz) phones. However, a subsequent study carried out to explore these results more thoroughly found that longer daily exposures to pulsed 800–915 MHz GSM RF radiation had no effect on testicular structure or function (Daşdağ et al, 2003).

24 Exposure of mice to the various low level RF fields broadcast from a commercial antenna park situated in mountainous countryside within Greece was reported to cause a drop in the number and size of litters (Magras and Xenos, 1997). Animals were exposed over a five-month period at both outdoor and indoor locations. The offspring of the exposed animals were larger, compared with those of control animals held in a laboratory, possibly as a result of the smaller litter sizes. However, the study was undermined by the lack of a matched control group (IEGMP, 2000), and the possibility that the observed changes were the result of other stresses in the environment and/or seasonal changes in day length cannot be discounted.

25 Generally, the effects of heat, including that generated by RF exposure, on the prenatal development of experimental animals are quite well understood and have been extensively reviewed (eg Edwards et al, 1995; Miller et al, 2002), although there is clearly a need for further investigation (Edwards et al, 2003). Animal studies have shown that, depending on the extent to which temperature is elevated above normal and the duration of exposure, heat either will have no perceptible effect or will kill pre-implantation stage embryos. Surviving embryos treated during pre-implantation go through gestation to form offspring having normal birth weight without an increased incidence of anomalies. Hyperthermia during organogenesis induces various developmental defects which can be related to the amount by which maternal body temperature is elevated (Edwards et al, 2003). Generally, statistically significant increases in the incidence of heat-induced abnormalities, mostly craniofacial and skeletal defects, are seen in the laboratory at maternal temperature increases of around 2–2.5 °C or more, mostly following exposure for tens of minutes up to an hour or so. Comparable results have been found following RF exposure that produce similar increases in maternal temperatures. For example, Lary et al (1983, 1986) and Brown-Woodman et al (1988) described relationships for similar threshold maternal temperature rise and duration for craniofacial and skeletal defects in rats exposed to 27.12 MHz radiation at thermal levels on day 9–9.5 gestation (neural tube closure during the early embryonic stage).

26 The developing central nervous system is considered to be the system most sensitive to raised maternal temperature (Edwards et al, 2003). This vulnerability arises from the limited number and restricted physical location of the cohorts of proliferating cells from which the brain arises and the precision required for the complex neuronal architecture essential to proper brain function. The proliferation and migration of neuronal cells during early corticogenesis in fetal mice, for example, was significantly reduced by brief (6–7 minute) hyperthermia sufficient to raise maternal temperature by about 4.5 °C (Hinoue et al, 2001). Reductions in the performance of learned tasks have been seen in mice repeatedly exposed at a similar level to heat during corticogenesis and in guinea pigs repeatedly exposed to a maximum elevation of maternal body temperature of about 2.0 °C during corticogenesis or glial cell proliferation (Jonson et al, 1976; Edwards, 1981; Shiota and Kayamura, 1989). However, temperature–duration thresholds for these effects remain poorly defined (Edwards et al, 2003).

27 Studies of the postnatal behavioural effects following exposure to RF radiation during pregnancy have been more equivocal. A series of studies carried out by Jensh and colleagues (Jensh et al, 1982, 1983; Jensh, 1984), summarised by Jensh (1997) and later reviewed by IEGMP (2000), reported a number of minor behavioural changes, such as reduced water T-maze performance by females but not males, in the offspring of rats exposed throughout pregnancy to 6.0 GHz at a whole-body SAR estimated to be about 7 W kg^{-1}. No effects were seen in the offspring of rats similarly exposed to 2.45 GHz or 915 MHz at whole-body SARs estimated to be about 2–4 W kg^{-1} (Jensh, 1997). Although an SAR of about 7 W kg^{-1} is usually thermogenic in rats under normal laboratory conditions (Gordon, 1987; Saunders et al, 1991), the author stated that maternal body temperature was not elevated by exposure to RF radiation in any of these studies.

28 More recently, two studies have examined the behavioural consequences of prenatal (and early postnatal) exposure to low level RF fields. Bornhausen and Scheingraber (2000) exposed freely-moving pregnant rats to pulsed 900 MHz GSM radiation continuously from day 1 to day 20 of gestation. Whole-body SAR (of dams) ranged from 0.0175 to 0.075 W kg^{-1}. Subsequent operant performance of offspring was assessed as adults using three differential schedules of reinforcement requiring either high or low rates of responses: exposure had no effect on task performance. Cobb et al (2000) exposed pregnant rats to ultra-wide band pulses (300 ps rise-time, 1.8 ns pulse width, average whole-body SAR 0.045 W kg^{-1}) for 2 minutes per day from day 3 to day 18 of gestation and from postnatal day 1 to day 10. Offspring were examined using an extensive battery of developmental landmarks and functional and behavioural tests, including water-maze performance and operant response. No statistically significant exposure-dependent effects were found except on three metrics (less vocalisation in exposed males, longer medial-to-lateral length of hippocampus, and lower mating frequency but without change in mating success). These differences were attributed by the authors to chance.

29 Animal studies have also shown that hyperthermia combined with treatment with endotoxins, arsenic, vitamin A, alcohol or aspirin is more effective in causing developmental defects than when administered alone (eg Edwards et al, 2003). A number of such studies that have sought to determine whether RF fields similar to those encountered in the workplace might potentiate the teratogenic effects of chemicals and solvents have been carried out by Nelson and colleagues (Nelson et al, 1991, 1994, 1997a,b). These authors exposed rats to 10 MHz RF radiation in combination with the

industrial solvent 2-methoxyethanol at various stages during pregnancy and examined the fetuses for external and internal malformations. These studies indicated that RF exposure and 2-methoxyethanol interacted synergistically to produce develop-mental abnormalities in exposed fetuses, but only at levels of exposure inducing significant rises in body temperature (IEGMP, 2000). The authors suggested that there was a need to consider combined exposure effects when developing both physical agent and chemical agent exposure guidelines.

30 Recent studies by this group (Nelson et al, 1999, 2001; Cheever et al, 2001) have provided support for the previous observation that 10 MHz RF radiation and 2-methoxy-ethanol act synergistically when maternal body temperatures are elevated to at least 41 °C for 60 minutes or more. In addition, the authors noted that salicylic acid (aspirin), which has also been shown to interact with heat (see above), did not act synergistically when combined with the above levels of RF heating (Nelson et al, 1999). Neither did methanol interact synergistically with this level of heat, although either agent increased resorption if administered on day 9 of gestation (Nelson et al, 2001).

Summary

31 Effects of heat and RF exposure on reproduction and development are summarised in Table 4.3.

32 Male fertility has long been recognised as susceptible to heat, and animal studies have confirmed a similar susceptibility to RF exposure at thermally significant levels; chronic exposure at non-thermal levels has generally been without effect. Preliminary reports by one group of workers of potentially detrimental effects of chronic mobile phone radiation on male fertility were not confirmed by a later, more thorough investigation. The results of an earlier report of reduced litter size in mice, potentially but not necessarily attributable to reduced male fertility, following prolonged indoor and/or outdoor exposure to RF radiation generated by a variety of local transmitters, was undermined by a lack of appropriate controls.

33 Significant heating is known to be teratogenic in animals and RF-induced hyper-thermia will induce similar developmental abnormalities. The developing nervous system seems most susceptible to insult, and mildly thermogenic levels of RF exposure may induce subtle behavioural changes in offspring. However, postnatal behaviour was unaffected following exposure to non-thermal levels of GSM-type RF radiation. RF-induced hyperthermia, like whole-body heating, may also act synergistically with various drugs and chemicals to induce developmental abnormalities, but only when biologically significant rises in maternal temperature are induced.

NEUROBEHAVIOURAL EFFECTS

34 The brain and nervous system have long been considered sensitive targets for the potential effects of exposure to low level RF fields. The possibility that exposure to RF fields may affect neurobehavioural function in animals has been explored from a number of perspectives using a wide range of exposure conditions. There have been sporadic reports of field-dependent effects using fields too weak to engender significant heating, but none has been firmly established. These studies have been reviewed by Hermann and Hossman (1997), Pakhomov et al (1998), D'Andrea (1999) and Hossman and Herman (2003), and specific effects on learning and memory have been considered by Lai (2001).

TABLE 4.3 *Reproduction and development – heat and RF exposure*

Model	Exposure conditions	Results	Reference
Testicular function			
RF radiation			
Testicular structure and function, sperm count in Sprague-Dawley rats	9.45 GHz CW at a whole-body SAR of 1.8 W kg^{-1} for 1 h per day for 13, 26, 39 or 52 days	Reduced epididymal sperm count; increased abnormal sperm	Akdağ et al, 1999
Testicular structure and function, sperm count in Sprague-Dawley rats	890–915 MHz pulsed GSM; 0.6 ms pulses at 217 pps for 3 min per day for 1 month at a whole-body SAR of 0.14 W kg^{-1}	Seminiferous tubule diameter significantly reduced	Daşdağ et al, 1999
Testicular structure and function, sperm count in Sprague-Dawley rats	890–915 MHz pulsed GSM; 0.6 ms pulses at 217 pps for 20 min per day for 1 month at a whole-body SAR of 0.5 W kg^{-1} or less	No effects	Daşdağ et al, 2003
Reproductive outcome			
Litter number and size in BALB/c/f mice	RF fields from an 'antenna park' over a 5- month period at various outdoor and indoor locations	Reduced number and size of litters compared to laboratory controls	Magras and Xenos, 1997
Embryo/fetal development			
Heat			
Pregnant mice exposed to heat during corticogenesis	Maternal temperature elevation by 4.5–4.7 °C for 6–7 minutes	Significant decrease in brain weight and neopallium thickness	Hinoue et al, 2001
Pregnant mice exposed to heat during corticogenesis	Maternal temperature elevation by 4.5–4.7 °C for 6–7 minutes once or twice daily during days 12–15 of gestation	Significantly reduced performance of T-maze and shuttle box tasks	Shiota and Kayamura, 1989
Pregnant guinea pigs exposed to heat during corticogenesis or glial cell proliferation	Maternal temperature elevation 'spike' of 2.1 °C over 1 h heat exposure daily during days 20–24 or days 40–44 of gestation	Significantly reduced serial discrimination reversal learning task performance	Jonson et al, 1976; Edwards, 1981
RF exposure			
Pregnant rats exposed to RF	915 MHz CW at a whole-body SAR estimated to be 3–4 W kg^{-1} for 6 h per day throughout gestation	No effect on postnatal and adult behaviour	Jensh et al, 1982; Jensh 1997
Pregnant rats exposed to RF	2.45 GHz CW at a whole-body SAR estimated to be about 2–4 W kg^{-1} for 6 h per day throughout gestation	No effect on most tests of behaviour; exposed offspring more active in an open field test	Jensh et al, 1983; Jensh, 1997
Pregnant rats exposed to RF	6.0 GHz CW at a whole-body SAR estimated to be about 7 W kg^{-1} for 6 h per day throughout gestation	Exposed female offspring showed decreased learning in water T-maze test and decreased activity levels, whereas males showed increased activity levels	Jensh, 1984, 1997
Exposure of pregnant rats throughout gestation	900 MHz pulsed GSM; 0.577 pulses at 217 pps; at whole-body SAR of between 0.0175 and 0.075 W kg^{-1} continuously from day 1 to day 20 of gestation	No effect on operant task performance	Bornhausen and Scheingraber (2000)
Exposure of pregnant rats and postnatal exposure of the offspring	UWB (dominant frequency range 0.1–1 GHz) pulses of 1.8 ns pulse width at 1000 pps; 2 min per day at average whole-body SAR of 0.045 W kg^{-1} during days 3–18, or during this period and to postnatal day 10	No statistically significant effects except more stress vocalisation, longer hippocampus and lower mating frequency in exposed offspring	Cobb et al, 2000

Gene expression

35 A few studies have investigated if the induction of stress-related genes and their proteins increase following exposure to RF fields. These genes respond to various insults, including heat, and the most consistent effects have been reported following exposures at thermal levels (IEGMP, 2000; Zmirou, 2001).

36 Stagg et al (2001) exposed rats for two hours to pulsed 1.6 GHz radiation (typical of Iridium satellite phone signals) using a head-only exposure system that produced local SARs up to 5 W kg^{-1} in the brain. No significant increases in body temperature were recorded and no field-dependent increases in *fos*, *jun* and *odc* mRNA were observed. Similar results using the same signal had been reported previously by Morrissey et al (1999) in the mouse brain; increased *fos* expression was seen only at thermogenic levels of exposure. An earlier study by Fritze et al (1997a) reported a slight increase in *hsp-70* expression following thermogenic exposure of the rat brain to pulsed 900 MHz GSM RF radiation.

Blood pressure and the blood–brain barrier

37 Blood pressure is regulated via baroreceptor reflex mechanisms acting through the autonomic and central nervous system. Increases in blood pressure have been reported in one volunteer study by Braune et al (1998) with exposure to RF radiation emitted by a mobile phone. Lu et al (1999) reported that exposure to ultra-wide band pulses, which encompass a wide range of frequencies (mainly 0.1–1.0 GHz), produced long-lasting, systolic hypotension in exposed rats. The effect appeared robust, although the mechanism was unclear; individual pulses were reported to be below the auditory threshold for pulsed microwave radiation, suggesting that auditory perception and anxiety-related phenomena cannot provide an explanation.

38 The blood–brain barrier is a dynamic interface that regulates the composition of cerebrospinal and interstitial fluid bathing central nervous system tissue. Physically, the 'barrier' comprises endothelial cells lining the blood capillaries of the brain and spinal cord and epithelial cells lining the choroid plexuses of the ventricles. 'Tight' junctions between these cells restrict the otherwise normal exchange of molecules through extracellular pathways, enabling the endothelial and epithelial cells of the blood–brain barrier to regulate the exchange of molecules between the fluid compartments. However, the blood–brain barrier is relatively permeable in some regions.

39 About 20 years ago several studies reported that low level exposure to RF fields may alter the permeability of the blood–brain barrier and cause leakage of molecules from the blood into the cerebrospinal fluid (see Blackwell and Saunders, 1986). Such responses could produce severe and lasting consequences. However, better-conducted studies subsequently did not corroborate these results, and consistent changes in permeability were only found using SARs of about 7 W kg^{-1} or more, which produced significant heating (WHO, 1993, IEGMP, 2000; Krewski et al, 2001a; Zmirou, 2001). Immobilisation stress is also associated with changes in the blood–brain barrier; habituation to experimental conditions is therefore essential when animals are restrained during exposure.

40 Nevertheless, Persson et al (1997) and Salford et al (1997) reported that exposure of rats to 915 MHz fields increased the permeability of the blood–brain barrier to

endogenous albumin. Using a TEM cell, animals were exposed in groups of four either to a continuous wave field or to pulse modulated fields at pulse repetition rates between 4 and 217 Hz, and exposures lasted from 2 to 960 minutes at SARs ranging from 0.4–8 mW kg^{-1} to 1.7–8.3 W kg^{-1}. The number of animals showing increased permeability was reported to depend on both SAR and pulse modulation frequency but generally most exposures increased the leakage of albumin. Furthermore, the largest effects were reported using the weakest fields, and exposure to continuous wave fields was reported to produce a greater effect than pulsed fields. However, weaknesses of this study include insufficient description of the experimental and exposure protocols used, and the findings are difficult to assess.

41 A more recent paper from the same laboratory (Salford et al, 2003) reported that single, brief exposure of juvenile rats to pulsed 896 MHz fields for two hours at SARs between 0.002 and 0.2 W kg^{-1} caused increased blood–brain barrier permeability to albumin and neuronal damage throughout the brain (indicated by darkly staining neurons), especially in the cortex, hippocampus, and basal ganglia. However, there are a number of caveats with this study. These include the modest size of study, the wide age range of the rats, and insufficient descriptions of the dosimetry, experimental procedures and exposure protocols. In particular, the quantification of the pathological effects was also very subjective. In addition, the numbers of brain slices scored per animal were not revealed.

42 Other recent studies using rats or mice have failed to corroborate these results, and acute or prolonged exposure to the fields associated with mobile telecommunications has produced nothing more than negligible effects on albumin permeability. Using a head-only exposure system, Fritze et al (1997b) exposed rats to 900 MHz pulsed radiation at 217 Hz for four hours at local SARs in the brain of 0.3, 1.5 or 7.5 W kg^{-1}. The leakage of albumin across the blood–brain barrier was examined using immunohistochemical staining either at the end of exposure or seven days later. Small increases in permeability were observed in all treatment groups examined immediately after exposure, but these numbers only reached significance in the animals exposed at the highest SAR which represented a thermal challenge. No sustained increases in permeability were reported. Using a similar design of exposure system, Tsurita et al (2000) exposed the heads of rats to a pulsed 1439 MHz TDMA field for 1 hour each day, 5 days a week, for 2 or 4 weeks. The peak SAR in the brain was 2 W kg^{-1}. Permeability was assessed using immunohistochemical staining and the Evans blue dye injection method. Neither exposure period caused any discernible effect on the permeability of the blood–brain barrier. In addition, exposure had no apparent effect on body weight or on the Purkinje cells and granular cells in the cerebellum. As positive controls, both local cold injury of the skull or 2-hour irradiation at 20 W kg^{-1} produced detectable increases in blood–brain barrier permeability.

43 Finnie et al (2001) exposed mice to 898 MHz pulsed radiation at 217 Hz for 60 minutes at 0.4 W kg^{-1} using a well-characterised, whole-body exposure system. This system consisted of a cylindrical parallel plate with the animals restrained in clear acrylic tubes arranged radially around a dipole antenna. Exposure had no significant effect on blood–brain barrier permeability as assessed using immunohistochemical staining for albumin. Where leakage had occurred, it was mainly confined to the leptomeningeal blood vessels which have no recognised blood–brain barrier. The same

pattern of responses was reported by Finnie et al (2002) using long-term, repeated exposure. In this study, mice were exposed to 900 MHz pulsed radiation at 217 Hz for 60 minutes each day, 5 days a week, for 104 weeks, at whole-body SARs of 0.25, 1, 2 and 4 W kg^{-1}. Comparable, small numbers of extravasations were observed in the brains of exposed, sham exposed and freely moving control animals, but statistical analysis was not performed.

Neurotransmitters

44 Changes in various neurotransmitter systems have sometimes been reported in a number of isolated studies from different laboratories. Hermann and Hossman (1997) ascribed many of the reported changes to spurious temperature effects. The possibility that confinement or other stresses associated with exposure may produce changes in neurotransmitters levels, particularly in the cholinergic systems, should also be considered. Notwithstanding, an extensive series of experiments by Lai and colleagues (reviewed by IEGMP, 2000) has reported that cholinergic function and endogenous opioid activity in rats were affected by acute exposure to pulsed and continuous wave 2.45 GHz radiation at a whole-body SAR of 0.6 W kg^{-1} (Lai et al, 1987, 1992, 1996; Lai and Carino, 1998).

45 Using semi-quantitative immunochemistry and image analysis to assess neurotransmitter content, Mausset et al (2001) reported that exposure to pulsed 900 MHz fields at 4 W kg^{-1} reduced the cellular GABA content in the Purkinje cells layer in the rat cerebellum. Similar, but more extensive, effects were observed following exposure to continuous wave fields at 32 W kg^{-1}. The magnitude of the SARs used suggests that thermal effects may have contributed towards these changes.

46 RF-induced changes in neurotransmitter activity could cause detectable changes in the electroencephalogram (EEG). Ivanova et al (2000) recorded the EEG from two awake cats following repeated one-minute exposures to a 980 MHz field pulsed at 12 or 27 Hz. The power density was 300–500 mW m^{-2}, no SAR was given. Variable increases in the spectral power of the 12–18 Hz band (with respect to the 25–40 Hz band) after the first exposure were reported, although any effects were much reduced or absent after 20 exposures. No consistent changes were observed at any time in the 5–8 Hz band. The same pattern of transient responses was reported using an auditory stimulus (at 70 dB). While some direct neurophysiological effect was possible, the observed responses also suggested that the RF effects might have reflected orientation or other responses caused by field-induced auditory perception of the field.

47 Testylier et al (2002) reported that exposure to RF fields caused sustained decreases in acetylcholine release from the rat hippocampus. Animals were exposed during the day for 1 hour to 2.45 GHz continuous wave radiation or exposed at night to 800 MHz radiation modulated at 32 Hz. Acetylcholine release was continuously measured by microdialysis using an implanted membrane in the CA1 region of the hippocampus. No effects were seen using 2.45 GHz at 3.26 W kg^{-1} but exposure at 6.52 W kg^{-1} significantly decreased acetylcholine release for several hours after exposure. Similarly, 1-hour exposure to pulsed 800 MHz radiation at 0.3 W kg^{-1} had no effect, but exposure for 14 hours beginning at 17:00 hours temporarily disrupted the normal pattern of acetylcholine release. Exposed animals failed to show the normal

nocturnal rise in acetylcholine levels, especially between 23:00 and 04:00 hours when the animals are most active. This result appears consistent with those previously reported by Lai and colleagues.

Learned behaviours

48 It has long been recognised that exposure to RF fields at thermal levels may affect performance of learned tasks by animals (WHO, 1993). Nevertheless, the possibility that low level exposure may engender behavioural or cognitive changes in animals under certain circumstances cannot be ruled out: too few tasks and exposure conditions have been examined to formulate definitive conclusions at this time (D'Andrea, 1999).

49 Recent studies have investigated the effects of RF radiation on spatial memory in rodents. These have produced inconsistent results. Initial reports suggesting large field-dependent deficits in task performance by rats exposed to pulsed 2.45 GHz fields at 0.6–1.2 W kg^{-1} (Lai et al, 1994; Wang and Lai, 2000) were not confirmed in studies using mice exposed to pulsed 900 MHz radiation at 0.05 W kg^{-1} (Sienkiewicz et al, 2000). More recently, Dubreuil et al (2002, 2003) exposed rats to pulsed 900 MHz fields for 45 minutes using a head-only system before daily testing on various spatial memory tasks (performed using a radial-arm maze or a dry-land version of the Morris water maze) or on an object recognition task. No consistent effects on the performance of any task were seen using average SARs in the brain of either 1 or 3.5 W kg^{-1}.

50 A similar lack of effect on spatial reversal learning in a T-maze was reported by Yamaguchi et al (2003) following exposure of rats to pulsed 1439 MHz PDC radiation at non-thermal levels for either four days or four weeks. However, performance was significantly impaired by exposure that increased intraperitoneal temperature by up to 2 °C.

Summary

51 Studies investigating the effects of RF fields on the nervous system and behaviour are summarised in Table 4.4.

52 Studies have continued to investigate the possible effects of RF fields on the brain and nervous system in animals. Despite sporadic reports of positive effects, most studies have not reported any field-dependent responses either in gene expression or in increased permeability of the blood–brain barrier. One study reported a long-lasting, systolic hypotension in rats following brief exposure to ultra-wide band pulsed RF radiation. The evidence from several laboratories indicates that changes may be induced in cholinergic activity in the brain following intense exposure. Such changes might predict effects on spatial learning and memory, but the evidence for this is equivocal: two studies from one laboratory have reported deficits in performance of spatial memory tasks using pulsed microwaves, but field-dependent changes were not confirmed in two independent studies using GSM signals. In addition, significant deficits on the performance of a related task were seen only when exposure increased body temperature by 2 °C. Nevertheless, few tasks and exposure conditions have been examined and the available results do not rule out the possibility that microwaves may engender subtle cognitive or behavioural changes in immature or adult animals.

TABLE 4.4 *Neurobehavioural effects*

Model	Exposure conditions	Results	References
Gene expression			
Genomic response in rat brain tissue immediately following *in vivo* exposure viz: *hsp-70*, *fos* and *jun* mRNA and their protein products assayed 24 h after exposure	900 MHz CW or pulsed GSM; 6 ms pulses at 217 Hz pps for 4 h at brain SARs of 0.3 or 1.5 W kg^{-1} (pulsed) or 7.5 W kg^{-1} CW	Slight increase in *hsp-70* expression at the highest SAR (7.5 W kg^{-1}) but no effects on Hsp-70 protein expression or any other exposure-related effects	Fritze et al, 1997a
Fos mRNA in the mouse brain	1.6 GHz CW or pulsed (Iridium signal); 9.2 ms pulses at 11 pps for 1 h at average brain SARs of ~0.3–11 W kg^{-1}	Increased *fos* expression in stress responsive and thermoregulatory parts of the brain at average brain SARs ≥ ~4 W kg^{-1}	Morrissey et al, 1999
Body temperature, *fos*, *jun* and *odc* mRNA levels in brain tissue and stress-related plasma hormone levels in Fischer rats	1.6 GHz pulse modulated (Iridium signal); 9.2 ms pulses at 11 pps for 2 h at brain SARs of 0.16, 1.6 and 5 W kg^{-1}	No effect on body temperature, gene expression or plasma hormone levels compared to sham values	Stagg et al, 2001
Blood pressure and the blood–brain barrier			
Heart rate, systolic, mean and diastolic pressure in rats 45 min to 4 weeks after exposure	UWB (dominant frequency range 0.1–1.0 GHz) pulsed radiation; 1 ms pulses with a rise-time of about 200 ps at 500 Hz or 1000 pps for 6 min. Whole-body SAR 0.07 or 0.12 W kg^{-1}, respectively	A significant decrease in arterial blood pressure but not heart rate in both exposed groups. The hypotension persisted for up to 4 weeks after exposure	Lu et al, 1999
Endogenous albumin and fibrinogen immunohistochemical staining in rat brain tissue	915 MHz CW or pulse modulated, either 0.57 ms pulses at 4, 8, 16 or 217 pps, or 6.6 ms pulses at 50 pps, for 2–960 min at whole-body SARs between 0.4–8 mW kg^{-1} and 1.7–8.3 W kg^{-1}	Increase in albumin permeability at different combinations of SAR and modulation; results for fibrinogen not presented	Persson et al, 1997; Salford et al, 1997
Cresyl violet or albumin immuno-histochemical staining in rat brain tissue 'about' 50 days after *in vivo* exposure	898.4 MHz pulsed GSM; 0.6 ms pulses at 217 pps for 2 h at a whole-body SAR of 2, 20 or 200 mW kg^{-1}	Increased presence of albumin and darkly staining neurons in brain tissue of exposed animals	Salford et al, 2003
Albumin immunohistochemical staining in rat brain tissue immediately or 7 days after *in vivo* exposure	900 MHz CW or pulsed GSM; 6 ms pulses at 217 Hz pps for 4 h at brain SARs of 0.3 or 1.5 kg^{-1} pulsed or 7.5 W kg^{-1} CW	Increased extravasation of albumin immediately after exposure at 7.5 W kg^{-1} but not 7 days later	Fritze et al, 1997b
Evans blue or albumin immuno-histochemical staining, and cerebellar Purkinje cell numbers in rat brain tissue exposed *in vivo*	1439 MHz pulsed PDC; 6.7 ms pulses at 50 pps for 1 h per day for 10 or 20 days at a brain SAR of 0.2 W kg^{-1}	No effect on blood–brain barrier integrity or Purkinje cell number	Tsurita et al, 2000
Albumin immunohistochemical staining in mouse brain tissue exposed *in vivo*	898.4 MHz pulsed GSM; 0.6 ms pulses at 217 pps for 1 h at a whole-body SAR of 4 W kg^{-1}	No effect on blood–brain barrier integrity	Finnie et al, 2001
Albumin immunohistochemical staining in mouse brain tissue exposed *in vivo*	900 MHz CW or pulsed GSM; 0.6 ms pulses at 217 pps for 1 h per day, 5 days per week for 104 weeks at a whole-body SAR of 0.25, 1.0, 2.0 or 4.0 W kg^{-1}	No effect on blood–brain barrier integrity	Finnie et al, 2002

Model	Exposure conditions	Results	References
Neurotransmitters			
Neurotransmitter (GABA) content of rat cerebellar tissue following *in vivo* exposure	900 MHz pulsed GSM; 576 μs pulses at 217 pps for 2 h at brain SARs of 4 W kg^{-1} pulsed or 32 W kg^{-1} CW	Decreased stained area in one cell layer following pulsed RF exposure; reduced optical density in three cell layers following CW exposure	Mausset et al, 2001
Neurotransmitter (ACh) release in rat hippocampal tissue during and after exposure *in vivo*	2.45 GHz CW for 1 h during the day at a whole-body SAR of ~3 or 6.5 W kg^{-1}; or 800 MHz amplitude modulated at 32 Hz for 1 or 14 h overnight at a whole-body SAR of 0.3 W kg^{-1}	Exposure to 2.45 GHz at 6.5 W kg^{-1} for 1 h, or to 800 MHz for 14 h at 0.3 W kg^{-1} significantly reduced ACh release	Testylier et al, 2002
Learned behaviours			
Water-maze performance in rats following RF exposure	2.45 GHz pulsed; 2 μs pulses at 500 pps for 1 h twice per day for 3 days at a whole-body SAR of 1.2 W kg^{-1}	Reduced performance	Wang and Lai, 2000
Radial-arm maze performance in mice following RF exposure	900 MHz pulsed; 576 μs pulses at 217 pps for 45 min each day for 10 days at a whole-body SAR of 0.05 W kg^{-1}	No effect on performance	Sienkiewicz et al, 2000
Radial-arm maze, food location task, or object recognition task following RF exposure	900 MHz pulsed; 576 μs pulses at 217 pps for 45 min each day for 10–14 days at a brain SAR of 1 or 3.5 W kg^{-1}	No effect on performance of any task	Dubriel et al, 2002, 2003
T-maze reversal learning in rats following RF exposure	1439 MHz pulsed PDC; 6.7 ms pulses at 50 pps for 4 day or 4 weeks at a brain SAR of 7.5 W kg^{-1} and whole-body SAR of 1.7 W kg^{-1} or brain SAR of 25 W kg^{-1} and whole-body SAR of 5.7 W kg^{-1}	No effect on performance at the lower level of exposure; a reduction at the higher, thermally significant, level	Yamaguchi et al, 2003

CONCLUSIONS

53 In order to put into context the implications of the studies using animal models published since the completion of the IEGMP report, they need to be evaluated against the conclusions of that report.

54 Firstly, considering the carcinogenic potential of RF radiation, IEGMP concluded that 'the balance of evidence suggests that at normal temperatures (consistent with exposures below guidelines) RF fields do not induce mutation'. IEGMP also concluded that 'RF exposure is unlikely to act as tumour initiator. Further, a variety of cancer studies using animals have sought evidence of an effect of RF exposure on spontaneous or natural cancer rates, the enhancement of the effects of known carcinogens or effects on the growth of implanted tumours. However, they have provided equivocal evidence for an effect on tumour incidence'. The evidence provided by the more recent studies both strengthens these conclusions and more clearly indicates that RF radiation does not increase the incidence of either spontaneous or induced tumours (for both mobile phone and other frequencies).

55 Secondly, considering the possible reproductive and developmental effects of RF radiation, IEGMP concluded that 'there is no convincing evidence from studies of rodents that exposure to RF fields at levels associated with mobile telecommunications poses any risk for the fetus or for male fertility'. The new evidence fully supports this conclusion, and reproductive or developmental effects would only be expected following RF-induced hyperthermia.

56 Finally, with regard to the effects of RF radiation on the nervous system, IEGMP concluded that, 'the most consistent evidence indicates that changes in neuronal excitability, neurotransmitter function, and innate and learned behaviours will occur when exposure induces significant heating, such that core body or local tissue temperatures increase by about 1 °C or more. The evidence for effects in the absence of heating is generally not consistent and convincing'. Further it was concluded that the 'well-conducted studies [on the blood–brain barrier] have not reported any effects'. The more recent studies corroborate these conclusions, especially with regard to the blood–brain barrier and learned behaviours, although some uncertainties remain regarding the effects of RF fields on neurotransmitter (acetylcholine) function.

57 Overall, the results of the RF studies performed with animals published since the IEGMP report support the original conclusions reached by IEGMP. However, the possibility of increased risk of cancer from exposure to RF radiation now seems less likely.

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5 Human Brain Activity and Cognitive Function: Recent Experimental Studies

1 The IEGMP (2000) report reviewed studies investigating the effects of mobile phone signals on brain activity or cognitive performance that had been published as of early 2000. In respect of brain (EEG) activity, the report concluded that, while findings were inconsistent, the balance of the evidence favoured the view that mobile phone signals at exposure intensities within international guidelines (ICNIRP, 1998) produced reliable changes in brain activity. A similar conclusion was reached in respect of cognitive performance: whereas inconsistencies remained, findings from three studies (Preece et al, 1999; Koivisto et al, 2000a,b) suggested that exposure to low intensity mobile phone signals gave rise to a slight shortening of reaction time on certain cognitive tasks, in the absence of an effect on error rates.

2 This chapter reviews relevant studies published since the completion of the IEGMP report, namely those studies concerned with direct effects of mobile phone signals on cognitive function and electrical measures of brain activity. Indirect effects, such as distracting effects of mobile phone conversations during driving, are not covered.

BRAIN ACTIVITY

3 Hietanen et al (2000) recorded resting EEGs from 19 volunteers during sham exposure, and exposure to signals from five different mobile handsets (analogue and GSM at 900 and 1800 MHz) operating at full power and positioned over the left side of the head. Specific (energy) absorption rates (SARs) were not given, but peak power was reported as between 1 and 2 W. Statistical analysis of spectral parameters of the EEG revealed an effect in only one frequency band in one exposure condition. The authors attributed this finding to chance.

4 Lebedeva et al (2000) recorded EEGs from 24 subjects during sham exposure and exposure to a 900 MHz signal (quoted intensity 0.6 W m^{-2}) directed at 'the back of the head'. The EEG was quantified by indices representing the 'dimensional complexity' of the signals; these were reported to vary significantly as a function of exposure condition, leading the authors to conclude that their chosen measure of EEG was more sensitive to the effects of radiofrequency (RF) signals than conventional indices. It should be noted, however, that the results of this study were reported in the absence of almost any information about how the data were analysed statistically, and with no information about levels of statistical significance.

5 Krause et al (2000) investigated 'event-related desynchronisation' of the EEG elicited by the visual presentation of letters during an '*n*-back' working memory task. Twenty-four subjects were employed, using an on/off single-blind procedure with a 900 MHz GSM signal (2 W peak output) transmitted through a handset positioned over the right side of the head. Exposure effects were observed in two specific bands of the EEG spectrum, at 6–8 and 8–10 Hz, although for 'target' letters only. There were no exposure effects on the behavioural measures of error rate and reaction time (cf Preece et al, 1999; Koivisto et al, 2000a,b). The authors concluded that, as in their previous study, the

findings suggested that RF effects on the EEG are most prominent during active cognitive processing.

6 Jech et al (2001) studied EEGs in 22 patients with narcolepsy. In 17 of these patients brain activity (event-related potentials) was studied during a visual 'oddball' task. In this task, rare horizontally-striped 'targets' (the oddballs) were interposed among presentations of more frequent non-targets (vertical stripes). Both classes of stimulus could occur either in full field, or restricted to one or other side of the visual field. Exposure was double-blind, with sham exposure and exposure conditions occurring on separate days (ordering of conditions was counterbalanced). Recordings were obtained during exposure, which took the form of a 900 MHz GSM signal transmitted from a commercial headset mounted over the right ear; the SAR was estimated to be 0.06 W kg^{-1}.

7 No effects of exposure were found for any measure of sleep behaviour or EEG. However, exposure was found to enhance the amplitude of two components of the brain's response to the oddball stimuli ('N2' and 'P3a' components), but only when the stimuli were presented to the right half of the visual field. This effect was most marked in waveforms from right hemisphere electrodes. In addition, exposure was found to shorten reaction time to both stimulus classes by approximately 20 ms.

8 These findings add to previous reports (IEGMP, 2000) of such effects on cognitive and brain function of RF exposure within ICNIRP (1998) guidelines. One caveat concerning the generality of the findings arises from the nature of the study sample, which was composed exclusively of narcoleptic patients, the majority of whom were medicated. It is possible, therefore, that the findings reflect an unusual sensitivity to RF exposure in such individuals, although this would not detract from their importance in demonstrating that low level RF exposure can lead to biological effects.

9 Croft et al (2002) recorded EEGs from 24 subjects in a single-blind on/off design, focusing on both event-related desynchronisation during an auditory discrimination task and parameters of the resting EEG. Exposure was via a 900 MHz GSM handset positioned over the midline posterior scalp. As confirmed by personal communication (RJ Croft, 10 October 2002), the phone was operated in 'listening' mode and therefore gave rise, due to discontinuous transmission (DTX), to low intensity emissions only (estimated by the authors to have an average power of 3–4 mW, some two orders of magnitude lower than that employed in most previous studies employing GSM handsets). Nevertheless, the authors reported significant exposure effects on both event-related desynchronisation and resting EEG parameters, although there was no effect on task performance. Since several of these effects were dependent on time, the authors concluded that the RF signal in this study had only an indirect effect on brain activity, rather than directly altering the neural circuits that generate the EEG pattern. Should these findings prove reliable, they would indicate an effect on brain function of mobile phone signals even when the intensity was markedly less than current guidelines. In the meantime, the results must be interpreted with caution, particularly given that the study was not double-blind.

10 Huber et al (2002) studied the effects of electromagnetic field signals similar to a GSM phone on regional cerebral blood flow measured by positron emission tomograph (PET), and on both sleeping and waking EEG. In the PET study, a 900 MHz signal was pulse modulated by extremely low frequency fields at 2, 8, 217 and 1736 Hz and corresponding harmonics, to approximate the spectrum of a GSM mobile phone signal. The

signal was delivered by two planar antennas to the left side of the head. The peak SAR was estimated at 1 W kg^{-1}. Thirteen subjects were tested in exposed and sham exposed conditions in counterbalanced order, using a within-subjects double-blind design. At least 1 week elapsed between the two tests. In each test, regional cerebral blood flow (rCBF) was measured over three 1-minute periods, starting 10, 20 and 30 minutes after completion of a 30-minute exposure to a pulse modulated electromagnetic field or sham exposure. rCBF is a reliable marker of neural activity in a local brain region. Subjects were asked to count silently during the scans, to balance cognitive function across scans. The results showed a significant increase in rCBF in the dorsolateral prefrontal cortex of the left (exposed) brain hemisphere. This brain area is known to be involved in working memory, which may be impaired by electromagnetic field exposure (Koivisto et al, 2001b). However, the result could also reflect differences between conditions in silent counting, since no independent measure of counting performance was obtained. It remains unclear why rCBF differences were seen in quite specific frontal regions of the brain, despite an exposure which presumably covered the entire left hemisphere.

11 Huber et al (2002) also studied effects of the same exposure on the EEG. The modulation components were as in their PET study. This was compared with a continuous wave version of the same signal and with sham exposure. The left side of each subject's head was exposed to each of these signals for 30 minutes on three separate evenings. Subjects then slept while their EEG was monitored. A double-blind design was used. Pulse modulated, but not continuous wave, electromagnetic fields produced a significant increase in alpha-wave (12.25–13.5 Hz) EEG activity (known as sleep spindles owing to their typical appearance on EEG recordings) in ensuing sleep, without changing other aspects of EEG or sleep behaviour. Analysis of individual EEG spindles showed greater spindle amplitude in pulse modulated electromagnetic fields than in either continuous wave electromagnetic field or sham exposure conditions. This effect did not diminish during the course of sleep The mechanism of such enduring effects is unclear. Finally, the effects of pulse modulated electromagnetic fields on the EEG, although statistically reliable, are small relative to the normal variation in EEG activity during sleep.

12 Taken together, the studies by Huber et al suggest a direct effect of pulse modulated electromagnetic fields on the normal activity of the brain, and particularly of the spontaneous oscillatory activity of networks of neurons. This effect appears to outlast the period of exposure. However, the mechanism of the effect remains unclear, nor is it clear whether the effects on neural oscillations and on rCBF are related or independent effects. Finally, these studies contained no measures of cognitive performance, so the impact on brain function of the changes induced by pulse modulated electromagnetic fields is unclear, as is their impact on health.

COGNITIVE FUNCTION

13 Edelstyn and Oldershaw (2002) employed a between-subjects design (n = 19 per group) to assess the effects of mobile phone signals on six common neuropsychological tests (digit and spatial span, forwards and backwards, serial subtraction, and verbal fluency). As confirmed by personal communication (N Edelstyn, 10 and 13 September 2002) exposure (single-blind) was effected by requiring subjects to hold a 900 MHz GSM

phone to their left ear and to answer a series of questions posed by the experimenter, who was in the same room. Exposure duration was for a total of 30 minutes, although subjects were not exposed while undertaking the neuropsychological tests. In addition, exposure would not have been constant during the period because of DTX. No dosimetry was calculated. Subjects were blinded to exposure condition (exposed vs sham) by covering the phone display so that it could not be determined whether the phone was on or off. Testing was undertaken in a pre-exposure baseline period, and 15 and 30 minutes after exposure. Exposure effects were inferred on the basis of statistical analysis of difference scores in performance on successive test periods (baseline – test 1; test 2 – test 1). The main effects of exposure group were found for digits forward, serial subtraction, and spatial backwards; in addition, group x time interactions were reported for digit span forward and spatial span backwards (not, as stated in the article, serial subtraction; N Edelstyn, personal communication, 10 September 2002). These effects were reported to take the form of greater improvements in performance between the baseline and subsequent periods for the exposed group (unfortunately, the actual data were not reported), and the authors interpreted their findings as being consistent with those of Preece et al (1999) and Koivisto et al (2000a,b). Their experimental procedures leave room for doubt, however, as to whether subjects in the exposed group were treated equivalently to the controls, as well as whether the subjects were unaware of handset status.

14 Smythe and Costall (2003) tested performance on a verbal memory task in three groups of healthy students. All subjects studied a list of 12 words, arranged in a pyramidal spatial shape, for 3 minutes. Subjects then performed a distracter task (reading aloud) for 12 minutes, and were asked to recall the word list, placing each word in the spatial location seen previously. Subjects returned 7–8 days later, and repeated the recall phase of the task. The subjects were assigned to three exposure groups. The 'active' group held an Ericsson A2618s mobile phone to their left ear during the study phase only. For the 'inactive' group, the phone was switched off. The phone operated at 1800 MHz, and induced an SAR of 0.79 W kg^{-1}, presumably measured as a local peak, according to the manufacturer's figures. The actual SAR during the tests was not measured but is likely to have been very low due to DTX. An additional 'no phone' control group did not hold the phone, and was not exposed. Since this last group was effectively unblinded, the key statistical comparisons were between the active and inactive exposure groups.

15 The results showed that the 15 male subjects in the active group tended to recall more words than males in the inactive control group, although this effect did not reach conventional significance levels. They also made significantly fewer errors in spatial placement of correctly remembered words. These effects were confined to immediate recall. There were no effects of exposure condition at delayed testing, suggesting an effect on short-term rather than long-term memory. There were no significant effects in the female subjects.

16 An improvement in immediate memory following mobile phone exposure seems consistent with previous reports of shorter reaction times (Koivisto et al, 2000a,b), since speed and accuracy are closely related in such tasks. However, some aspects of the study of Smythe and Costall (2003) suggest a need for caution in interpreting their results. The number of subjects per group was relatively small, and it is unclear whether

the unusually large age range was balanced across groups, which weakens any comparison across groups. In addition, the experimenters were not blind between the 'active' and 'inactive' groups. Since subjects positioned and held the phone themselves, and since the phone was not driven by a quantified signal, the effective exposure is unclear, and could vary across groups. Finally, it is unclear why the facilitatory effect was sex-specific, suggesting this may be a chance finding in a subgroup. An attempt to replicate these effects in a larger, well-characterised sample would be valuable. Until then, this study alone cannot be taken as strong evidence for any direct effect of mobile phone signals on cognitive function.

17 Lass et al (2002) studied the performance of 100 Estonian students on three cognitive tasks. These were visual attention (searching for digits in pre-specified sequence within a random spatial pattern), short-term memory recall for visually-presented pictures, and a visual search test of sustained attention. Subjects were allocated randomly to an exposed or sham exposed group, and were tested single-blind. In the exposed group, a 450 MHz RF signal, amplitude modulated at 7 Hz with a 50% duty cycle, was amplified to a 1 W electromagnetic field output power, and guided to an antenna 10 cm from the right side of the head. The measured field power density was 1.58 W m^{-2}, and the SAR, estimated using anatomical models, was 0.0095 W kg^{-1}, too low to produce thermal effects. The authors do not specify the procedure for sham exposure.

18 Exposed subjects made significantly fewer errors on the memory recognition task than sham exposed subjects. In contrast, the trails task and visual search task, which require more effort and are more demanding, produced small and non-significant effects in the opposite direction, showing worse performance and greater inter-subject variability, in the exposure than the sham exposure group.

19 The authors suggested that the pulsed signal acted as a low level stressor (although their data provided no statistically reliable evidence for a drop in performance). They further suggested that the brain may over-compensate for this stress during easy cognitive tasks, leading to the improved accuracy in the relatively easy memory task. Effects of the electromagnetic field signal on cognitive performance may reflect strategic compensation by the brain. Previous studies have also reported electromagnetic field effects which vary with task difficulty (Koivisto et al, 2000a), but in those cases performance benefits were found only when the memory task was difficult. For this reason, the results and conclusions of Lass et al (2002) should be treated with some caution. In addition, the authors used different subjects for the exposure and sham exposure treatments: although these groups were quite large, and were said to represent a relatively homogeneous population, it was possible that psychological differences between the two subject groups were confounded with the exposure effect. In general, a within-subjects design in which each subject performs both exposure and sham exposure conditions is preferable to a between-subjects comparison in experiments of this kind.

20 Haarala et al (2003) replicated and extended the study of Koivisto et al (2000a). That study had suggested that exposure to a 900 MHz GSM signal could shorten reaction times in some cognitive tasks. The Haarala et al (2003) study reports an attempt by the same research team to replicate these effects, using a superior experimental design. The authors tested 64 subjects in two independent laboratories in Sweden and Finland. Each subject performed nine different cognitive tasks, which varied in difficulty, mainly

due to differences in working memory load and in the need to actively inhibit some responses while making others. Speed and accuracy of performance were measured on each task. Subjects performed the tasks in counterbalanced order in two sessions lasting 65 minutes on two successive days. They were exposed to electromagnetic fields during one session, and sham exposed in the other, in counterbalanced order. Participants and experimenters were unaware of the exposure condition.

21 The electromagnetic field was delivered by a 900 MHz GSM phone with DTX inactivated and the earphone removed. The mean power was 0.25 W, pulsed at 217 Hz with a pulse width of 577 μS. The average SAR was measured with a dosimetric assessment system as 0.88 W kg^{-1} averaged over 1 g, with a peak of 1.2 W kg^{-1}. The phone was held against the left side of the head by a rubber cap, in the standard position of use. The authors also measured the thermal effects of the phone on the skin in both exposure and sham exposure conditions. The thermal effects were small and the subjects were unable to discriminate between the exposure conditions using thermal cues.

22 The reaction times and error rates on all nine cognitive tasks were compared statistically. No reliable differences between exposure and sham exposure conditions were found, and the authors concluded that electromagnetic field exposure has either no effect or only small and unreliable effects on human cognitive function.

23 These findings are particularly noteworthy as they represent non-replication of an earlier report of facilitatory effects of electromagnetic field exposure on cognitive function (Koivisto et al, 2000a) that had considerable impact. The study reported here used a superior design to that employed in the earlier work, and their evidence therefore carries more weight. A comparison between the later findings and the earlier results underlines the importance of three key features of best scientific practice in this area: experiments should be double-blind, they should use an adequate sample size, and they should be replicated in an multicentre study.

24 Zwamborn et al (2003) compared the effects of whole-body exposure to 945 MHz GSM, 1840 MHz GSM, or 2140 MHz UMTS RF signals and sham exposure, experienced 3 m from a base station antenna (closer than is usual in the normal environment), on cognitive function and subjective reports of well-being in two groups: a group that had reported subjective complaints linked to GSM signals, and a control group. However, the two groups were not matched for age or other relevant factors. All exposures were well below ICNIRP guidelines. The study was double-blind; subjects performed four tests of cognitive function, namely reaction time, memory comparison, dual-tasking and filtering irrelevant information, during each exposure session. In addition, current subjective well-being, using a standard questionnaire, was reported immediately after each exposure session.

25 In the cognitive function tests, 900-MHz-type GSM signals were associated with significantly increased (ie slower) reaction times in the subjects with complaints, while UMTS-like signals significantly increased reaction times in control subjects. Performance of a memory comparison test was significantly faster, in control subjects only, during exposure to 1800-MHz-type GSM and UMTS signals compared to sham exposure. Visual selective attention appears to have been significantly impaired in both groups during UMTS exposure only. Two measures of dual-tasking performance were used: one measure showed significant changes with 1800 MHz GSM-type signals in the control group only, while the other was sensitive to 900 MHz GSM-type signals in the subjects

with complaints. In addition, both groups of subject reported significantly lower overall well-being following exposure to the UMTS signal only, compared to sham exposure.

26 The study appears carefully-conducted, well-designed and has reasonable statistical power. It suggests that some direct effects of RF signals on well-being and human cognitive function might exist. However, the authors did not state that they had used statistical adjustment for multiple comparisons between several exposure conditions. As a result, some of the comparisons between exposure and sham conditions which are reported as significant may not in fact be reliable. Furthermore, the pattern of the results on cognitive function was not consistent across the three RF signals, the four different cognitive tasks or the two study groups, which argues against a true effect. The reaction time data deserve special consideration. Although a previous study had reported faster reaction times during RF exposure (Koivisto et al, 2000a), the study by Zwamborn et al found significantly increased (slower) reaction times, but the groups were inconsistent regarding which RF signal produced such increases. However, the results did suggest a consistent effect of UMTS signals, but not GSM signals, on subjective well-being in subjects in both study groups. Since the study was double-blind, this result suggests that some RF signals might produce subjective symptoms in some individuals. In contrast, a previous study had reported no such effects (Hietanen et al, 2002). These inconsistencies leave it unclear whether any effect truly exists.

27 Lee et al (2001) compared the performance of 5th form schoolchildren, segregated according to mobile phone usage into two groups (users vs non-users, $n = 37$ and 35, respectively), on three 'paper and pencil' tests of cognitive function: symbol–digit matching, Stroop test, and trail making. Mobile phone users were selected according to self-reported usage (indexed as time with phone x average minutes used each day), and comprised the 37 heaviest users meeting other inclusion criteria. The controls were age- and sex-matched, but it is unclear whether they were matched for intelligence (no such background data were reported). The performance of the user group was found to be significantly better than that of the controls on both versions of the trails test (version A – where it is merely necessary to join up a series of randomly displayed numbers in the correct order; version B – where numbers and letters must be joined in alternation). The authors interpreted their findings as evidence that mobile phone use facilitated 'attentional' function. This conclusion can be questioned on at least two grounds. First, the finding of an effect on both versions of the trails task is more consistent with an interpretation in terms of enhanced sensorimotor function than attention. More seriously, as was acknowledged by the authors, the effect may reflect the influence of one or more variables confounded with phone use, rather than a direct effect of mobile phone signals on cognitive function. This study therefore does not provide unambiguous evidence of a direct effect of mobile phone signals on cognitive function.

SUMMARY

28 The findings from the studies published since the completion of the IEGMP report on effects of RF signals on human brain activity and cognitive function are inconsistent. In the case of EEG studies, both negative and positive results have been reported. The studies finding positive effects of electromagnetic field exposure are inconsistent

regarding which features of the EEG pattern are affected. Moreover, the mechanism by which electromagnetic fields might influence EEG patterns remains unclear. The body of evidence regarding direct RF exposure effects on cognitive function remains inconsistent. Some well-conducted studies have reported significant changes in cognitive functions due to RF exposure, while others have found no significant effects. Among those studies reporting changes, both facilitatory and inhibitory effects of RF exposure have been reported. Overall, no single, clear effect of RF exposure on cognitive function can be identified.

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6 Non-cancer Epidemiology and Clinical Research

1 Information about the potential adverse health effects of radiofrequency (RF) radiation comes not only from laboratory experiments of the types described in Chapters 3–5, but also from clinical and epidemiological observations in exposed people. Epidemiological data relating to possible risks of cancer are reviewed in Chapter 7. This chapter focuses on other health outcomes that have been linked with exposure to RF radiation. In general, the chapter covers studies published before and since the IEGMP (2000) report in similar depth. The relation of various disorders to RF radiation from visual display units (VDUs) was considered in an earlier report from the Advisory Group (AGNIR, 1994), and therefore VDU studies evaluated before then have not been re-examined in detail.

EFFECTS OF SHORT-TERM HIGH EXPOSURE

2 A number of published reports describe incidents in which people have experienced short-term exposures to levels of RF or microwave radiation well above currently recommended exposure limits. These unusual exposures have occurred in various circumstances including work close to radio and radar antennas while they were transmitting, and failure of protective interlocks on microwave ovens. In some cases only part of the body was irradiated.

3 As would be expected, sensations of warming are frequently reported (Daily, 1943; Williams and Webb, 1980; Forman et al, 1982; Schilling, 1997, 2000; Reeves, 2000; Hocking and Westerman, 2001), and these have sometimes been associated with skin erythema and evidence of tissue damage. Other acute symptoms have included headache (Forman et al, 1982; Schilling, 1997, 2000; Reeves, 2000; Hocking and Westerman, 2001), fatigue (Schilling, 2000; Hocking and Westerman, 2001), vertigo (Forman et al, 1982), eye irritation (Forman et al, 1982; Reeves, 2000), photophobia (Forman et al, 1982), blurred vision (Hocking and Westerman, 2001), indigestion (Forman et al, 1982), diarrhoea (Schilling, 1997, 2000), anxiety, insomnia, and emotional lability (Forman et al, 1982), and numbness and paraesthesiae (sometimes with demonstrable impairment of nerve conduction) (Tintinalli et al, 1983; Marchiori et al, 1995; Schilling, 1997, 2000). In some cases, abnormalities have persisted for months or even years (Marchiori et al, 1995; Schilling, 1997, 2000; Hocking and Westerman, 2001).

Conclusions

4 It is well established that acute exposure to RF radiation can cause thermal injury to tissues. However, such injuries have not been shown to occur from exposures below current guideline levels in the UK. It is unclear whether the psychological symptoms that have been described reflect direct injury to the central nervous system or an indirect effect of stresses associated with the exposure incident.

MICROWAVE HEARING

5 It has been well documented that people can hear buzzing, clicking or popping sounds when exposed to pulse modulated fields with frequencies between about 200 MHz and 6.5 GHz (Barron et al, 1955; ICNIRP, 1998). The phenomenon has been reported with average exposures as low as 4 W m^{-2} (Frey, 1961), and a threshold for perception of about 100–400 mJ m^{-2} has been reported for pulses of duration less than 30 μs at 2.45 GHz (ICNIRP, 1998). Mechanical vibrations are induced through minute thermoelastic expansion in the soft tissues of the head, and are transmitted to the cochlea by bone conduction (IEGMP, 2000). The effect depends on the magnitude and rate of the transient temperature increases that are produced by the RF pulses, and in theory could occur over a wider range of frequencies than described above. The perception of sound that results could be annoying, but would not be expected to cause any long-term health effect.

Conclusions

6 There is convincing evidence that pulse modulated RF radiation with frequencies between 200 MHz and 6.5 GHz can cause auditory stimulation at average exposure levels as low as 4 W m^{-2}. This results from thermoelastic expansion of tissues in the head as a consequence of minute fluctuations in temperature. Although the resultant perception of sound might be considered a nuisance, there is no reason to suspect that it has any long-term adverse impact on health.

CATARACT

7 The possibility that microwave radiation might cause cataracts has long been a concern because the lens of the eye does not have a blood supply through which heat can be dissipated. A number of early surveys sponsored by the US Air Force were reviewed by Odland (1972). Some of these suggested more prominent posterior polar lens changes in individuals with posible occupational exposure to microwaves, but there was no evidence of more serious eye disease. Potentially more important lens changes were observed, however, among 35 individuals involved in incidents of acute over-exposure to microwaves (200–2000 W m^{-2}) at a US Air Force facility (LaRoche et al, 1970). Of these, 12 were said to exhibit 'typical' microwave lens changes, characterised initially by thickening and opacification of the posterior lens capsule, and eventually progressing to opacification of the lens itself.

8 To investigate the risk of clinically significant cataract, Cleary and colleagues searched the diagnostic indices of hospitals in the US Veterans Administration system and identified 2946 white male Army and Air Force veterans born after 1910 who had been treated for cataracts during 1950–62 (Cleary et al, 1965). They compared them with a control group of 2164 men whose hospital registration numbers were adjacent to those of the cases. History of work with radar was determined from the subjects' military records. After exclusion from the case group of congenital cataracts and cataracts associated with Down's syndrome, trauma and diabetes, the crude relative risk associated with radar work was 0.67. Furthermore, within three age strata, the highest relative risk was 1.02. No account was taken of potential confounding factors other than age. The study was powered to detect a doubling of risk.

9 Subsequently, the same authors carried out a cross-sectional survey of 736 workers with exposure to microwaves and 559 unexposed controls who were employed at the same locations (Cleary and Pasternack, 1966). The median duration of microwave work in the exposed group was 3.5 years. Each man underwent slit-lamp examination, with the examiner unaware of his exposure status. Abnormalities of the lens such as opacification, posterior polar defects, relucency and sutural defects were each graded to four levels, and summary 'eye scores' were derived. These scores were then regressed on exposure scores determined from each man's occupational history, with adjustment for age. Minor abnormalities, in particular posterior polar defects, tended to occur more frequently with exposure to microwaves, and their prevalence was related to duration of microwave work, and history of sensations of exposure such as cutaneous heating.

10 In the course of six-monthly eye screening at an American military base during 1968–71, workers were examined without knowledge of their exposure to microwaves (Appleton and McCrossan, 1972). In a comparison of 91 persons exposed to microwaves (in some cases since 1943) and 135 unexposed controls, no evidence was found of increased lens abnormalities.

11 In Sweden, 68 workers exposed to microwave radiation in the electronics industry were examined by two eye specialists, together with 30 unexposed controls (Aurell and Tengroth, 1973). The examining doctors were not aware of subjects' exposure status. At younger ages, there was a higher prevalence of lens opacities among the exposed workers, but the importance of this finding is reduced in so far as the study was stimulated by an observed excess of such abnormalities in a screening programme.

12 A survey of 841 men aged 20–45 years who were occupationally exposed to microwaves compared the prevalence of lens changes in 507 with higher exposures (2–60 $W\,m^{-2}$) and 334 with lower exposures (Siekierzynski et al, 1974a). After allowance for age, no significant difference was found, but the method of statistical analysis was poorly described.

13 Another cross-sectional survey compared the findings on ophthalmic examination in 417 workers exposed to microwave radiation at US Air Force bases and 340 unexposed controls (Shacklett et al, 1975). The examiner was unaware of the subjects' exposures. Abnormalities of the lens (opacities, vacuoles and posterior subcapsular iridescence) were classified according to pre-defined criteria, and while they increased in prevalence with age, they were not associated with exposure to microwaves.

14 In a study in the former Yugoslavia, ophthalmic and other investigations were carried out on 320 men aged 25–40 years, who had been exposed to pulsed microwaves from radar (generally at less than 50 $W\,m^{-2}$) for five to ten years, and 220 controls matched for age and social conditions (Djordjevic et al, 1979). No significant differences were found in the prevalence of lens opacities (0.9% in both groups).

15 There was no relation of lens changes to duration of radiation exposure in a survey of 121 Finnish radar workers (Castren et al, 1982). However, data on exposures were limited, and because the clinical assessment involved a two-stage process, the ascertainment of lens abnormalities may not have been complete.

16 In contrast, a survey in Australia found posterior subcapsular opacities on slit-lamp examination (conducted without knowledge of exposure status) in 11 of 53 radio linemen as compared with 3 of 39 age- and sex-matched controls (Hollows and Douglas,

1984). The linemen were exposed to microwave power densities measured at 0.8 to 39 560 W m^{-2}.

17 The earlier Advisory Group review of health effects from VDUs (AGNIR, 1994) concluded that there was no evidence at that time that work with VDUs caused cataracts. However, no long-term follow-up studies of cataract in VDU users have yet been reported.

Conclusions

18 The available epidemiological evidence on microwave radiation and cataract is of variable quality. Many of the published reports do not provide quantitative data on exposures, or on the reliability of the methods by which pathology in the lens was assessed. Where eyes were examined with knowledge of exposure status, there was potential for bias. Even where they were examined without such knowledge (as was the case in most studies), non-systematic misclassification of disease will have tended to obscure any increase in risk from microwave exposure. In some investigations there may have been unrecognised confounding (positive or negative) from differences in exposure to ultraviolet radiation in sunlight or differences in age distribution.

19 Some studies have suggested that minor defects in the posterior pole of the lens are found more frequently in workers exposed to microwave radiation, but this has not been a consistent finding, and the changes reported are of doubtful clinical relevance. Overall, there is no indication that clinically important cataracts occur with increased frequency in microwave workers.

MALE SEXUAL FUNCTION AND FERTILITY

20 A cross-sectional survey in Romania (Lancranjan et al, 1975) examined sexual function in 31 male technicians (mean age 33 years) who had been exposed to microwaves for 1–17 years at levels that were often in the range of hundreds to thousands of W m^{-2}. Of these, 22 (70%) reported reduced libido and disturbance of erection, ejaculation or orgasm, and abnormal spermatogenesis was observed in 23 (74%). Sperm counts were significantly lower than in 30 unexposed controls (mean age 34 years) as were counts of motile sperm. However, no significant differences were found in the urinary excretion of 17 ketosteroids. (No information was given about the repeatability of the sperm counts or whether they were assessed blind to exposure status.)

21 A survey of American soldiers compared semen analyses and blood levels of hormones in 30 artillerymen with potential exposures to lead, 20 operators of radar equipment, and 31 controls unexposed to lead or microwaves (Weyandt et al, 1996). The laboratory examination of semen included computer assisted sperm analysis (CASA), and was carried out without knowledge of subjects' exposure status. After adjustment for potential confounders, the radar operators had a lower mean sperm count than the controls ($1.3\ 10^7$ mL^{-1} vs $3.5\ 10^7$ mL^{-1}) and a lower percentage of motile sperm (32% vs 43%). However, no significant differences were observed in various other measures of sperm quality, nor in blood levels of luteinising hormone or free testosterone. The authors noted the possibility that soldiers with concerns about fertility problems were selectively recruited into the study.

22 This investigation was followed by a larger survey by the same group with a broadly similar design that included 33 soldiers with exposure to radar, 57 artillerymen and 103 controls (Schrader et al, 1998). No significant differences were found between the men exposed to radar and the controls for any of: serum and urinary follicle stimulating hormone and luteinising hormone; serum, salivary and urinary testosterone; semen analysis. The authors speculated that the exposures to radar may have been lower than in their earlier study.

23 A preliminary survey of 19 Danish military personnel exposed to microwave-emitting radar systems (maximal mean exposure 0.1 $W\,m^{-2}$ but with occasional short-term exposures up to 10 $W\,m^{-2}$) found that after adjustment for duration of sexual abstinence, their mean sperm count was 2.3 $10^7\,mL^{-1}$ lower than for 489 men from other occupational groups studied previously (Hjollund and Bonde, 1997).

24 Investigators in the USA compared 33 parameters of semen quality and serum levels of four sex hormones in 12 RF heater operators and 34 unexposed controls (Grajewski et al, 2000). Participation rates were low, especially in the control group (34.1%), and there were major differences in the ethnic origin of the exposed and control subjects. Minor differences were found in several measures of semen quality, and serum FSH (follicle stimulating hormone) levels were slightly higher in the RF-exposed operators, but the occurrence of these results in the context of multiple statistical testing suggests that the findings might have been due to chance.

Conclusions

25 The current evidence base on RF radiation and male sexual function is extremely limited. Three out of five published studies have suggested a reduced sperm count in exposed workers, but all of these investigations have been small, and one (Lancranjan et al, 1975) was of doubtful rigour.

FEMALE SEXUAL FUNCTION AND FERTILITY

26 A Polish survey in the 1960s of 118 women working with microwave generators was reported to indicate an increased frequency of cervicitis and menstrual disturbance (Higier and Baranska, 1967). However, it is unclear from the English summary how the expected rates were derived, whether the comparison took account of potential biases and confounders, and whether the excess was statistically significant.

27 More recently, an investigation of time to pregnancy was carried out among a cohort of Danish female physiotherapists (Larsen et al, 1991). Information about pregnancies and birth outcomes was obtained by linkage with registers of births and hospital in-patients, and interviews were conducted with women who had experienced spontaneous abortion (166 cases), stillbirth or death in the first year of life (18), low birthweight (under 2500 g) (44) or pre-term delivery (86), as well as a sample of those with pregnancies that did not fall into any of these categories. Among other things, the women were asked about time to pregnancy after cessation of contraception, and about their exposure to short-wave diathermy during the first month of pregnancy. The latter was characterised by a time-weighted exposure index. No clear relation was found between prolonged time to pregnancy (over six months) and occupational exposure to microwave radiation (odds ratio, OR, for highest vs lowest exposure category of 1.7; 95% confidence interval, CI, 0.7–4.1).

Conclusions

28 Only one epidemiological study of reasonable quality has addressed the impact of RF radiation on female fertility (Larsen et al, 1991), and the results are inconclusive.

SPONTANEOUS ABORTION

29 An early case report from the USA described a woman who miscarried following eight treatments with microwave diathermy during the first 59 days of pregnancy for chronic pelvic inflammatory disease (cited in Michaelson, 1982).

30 More recently, a nested case–control study of spontaneous abortion was conducted among a national cohort of some 5000 female physiotherapists in Finland (Taskinen et al, 1990). The cases were identified by linkage with a hospital discharge register and with clinical data on spontaneous abortions, and were compared with a sample of physiotherapists who had given birth to a normal child. (Where a woman had had several abortions or births during the study period, one pregnancy was selected at random.) Occupational exposures during the first three months of pregnancy were ascertained by postal questionnaire with response rates close to 90%. In an analysis based on 204 cases and 483 controls, spontaneous abortion was associated with use of ultrasound and physical exertion at work, and abortion after ten or more weeks' gestation was associated with use of deep heat therapies (especially short-wave diathermy). However, in a multivariate analysis that included potential confounders, the last association was not statistically significant.

31 In another case–control study, 146 Danish physiotherapists who had suffered spontaneous abortion were compared with a reference group of 259 physiotherapists with completed pregnancies (Larsen et al, 1991). No significant association was found with a time-weighted index of exposure to high frequency electromagnetic radiation from use of short-wave treatments during the first month of pregnancy (OR for highest vs lowest exposure category 1.4; 95% CI 0.7–2.8).

32 Following a postal survey of 42 403 female physiotherapists in the USA which collected information about pregnancy outcome and occupational exposures, a nested case–control study of spontaneous abortion was conducted in a subset of 6684 responders who reported ever having used microwave or short-wave diathermy at some time during employment (Ouellet-Hellstrom and Stewart, 1993). The 1753 case pregnancies were each matched with a control pregnancy in a mother of the same age (some mothers were sampled more than once as cases, controls or both). After adjustment for various potential confounders (including a variable for the number of previous fetal losses), there was an elevated risk of spontaneous abortion in women who were exposed to microwave diathermy during the six months before and three months after conception (OR 1.34; 95% CI 1.02–1.59). Moreover, risk increased with the number of exposures per month. However, no clear elevation of risk was apparent for exposure to short-wave diathermy during the same period (OR 1.07; 95% CI 0.91–1.24). [A subsequent letter pointed out that microwave diathermy is less penetrating than short-wave therapy and therefore would give a lower dose to the uterus early in pregnancy (Hocking and Joyner, 1995).]

33 The 1994 Advisory Group report on VDUs reviewed nine epidemiological studies of spontaneous abortion (AGNIR, 1994). Six of these investigations found no elevation of risk even in heavy users, and the report concluded on the balance of evidence that VDU use does not increase the risk of spontaneous abortion. No new studies on the relation of spontaneous abortion to use of VDUs have been published since 1994.

Conclusions

34 Although one case–control study has suggested a small elevation in the risk of spontaneous abortion among physiotherapists who used microwave diathermy around the time of conception, an association with short-wave or microwave therapy was not clearly apparent in two other investigations. Given the potential for recall bias in studies which ascertain exposures from subjects' personal recollection, the single positive finding is not a cause for concern. At the same time, current epidemiological evidence does not rule out the possibility that RF radiation could have a small effect on the risk of spontaneous abortion.

BIRTH OUTCOME AND CONGENITAL MALFORMATIONS

35 An early case–control study in Baltimore, USA, collected information about the parents of 216 children with Down's syndrome and an equal number of individually matched controls (Sigler et al, 1965). The main focus of the investigation was exposure to ionising radiation before the child was born, but, unexpectedly, there was a higher prevalence of exposure to radar among the case fathers (8.7% vs 3.3% of controls). This association disappeared, however, when the ascertainment of cases was extended to cover births over a longer period (Cohen et al, 1977).

36 A Swedish study compared the prevalence of birth outcomes in 2043 babies born to 2018 physiotherapists during 1973–78 with that expected from national rates (Källén et al, 1982). After adjustment for age, parity and hospital of delivery, the numbers of babies with gestation less than 38 weeks, birthweight under 2500 g, and major malformations were all less than expected, and the frequency of all malformations was close to expectation. However, in a nested case–control investigation that used a postal questionnaire to collect information about occupational exposures during pregnancy from 33 women whose babies were seriously malformed or died perinatally, 33% reported use of short-wave equipment often or daily as compared with 14% of 63 controls ($p = 0.03$). There was no obvious pattern to the diagnoses of the exposed cases. Exposure to microwaves was too rare for meaningful analysis.

37 A preliminary report of a register-based case–control study in Finland found no association between congenital malformations of the central nervous system, oral cavity, skeleton or cardiovascular system and exposure to non-ionising radiation (largely from microwave ovens) in restaurant staff during the first trimester of pregnancy (Kurppa et al, 1983). However, the authors indicated that their findings might be subject to revision because the classification of exposures had not yet been finalised.

38 A later Finnish study used the national register of congenital malformations to identify cases born to mothers who were physiotherapists (Taskinen et al, 1990). Each case was matched with five normal births in the same cohort of women, and occupational exposures during the first three months of the relevant pregnancy were

ascertained by means of a postal questionnaire (response rate close to 90%). In an analysis based on 46 cases and 187 controls that adjusted for several potential confounders, congenital malformations were associated with the use of short-wave equipment for over an hour per week (OR 2.3; 95% CI 1.1–5.2). However, there was no indication that risk increased with more frequent exposure.

39 The observation of a case cluster prompted a similar study of female physiotherapists in Denmark (Larsen, 1991). By linking union records with national registers of births, congenital malformations and hospital admissions, the investigators identified 57 cases of malformation and 267 referents randomly selected from non-cases. Information about occupational exposure to short-wave equipment during the first month of pregnancy was obtained through a blinded telephone interview (response rates above 90%). Positive associations were observed with duration and peak level of exposure, but these were weak and not statistically significant.

40 A further study based on the same cohort of Danish physiotherapists compared cases of birthweight under 2500 g (44 cases), birth at less than 38 weeks' gestation (86) and stillbirth or death in the first year of life (18) with control births that did not meet these case definitions (Larsen et al, 1991). Again, occupational exposures during the first month of pregnancy were assessed from blinded telephone interviews. Exposure to short-wave diathermy was associated with a significant reduction in the ratio of male to female births, only 4 of the 17 children born to mothers with the highest time-weighted exposures being boys. However, associations for the other birth outcomes examined were based on small numbers of exposed cases and were not statistically significant.

41 In a postal survey completed by 2263 female members of the Swiss Federation of Physiotherapists (response rate 79.5%), information was collected about the sex and birthweight of all children, and about the use of short-wave and microwave equipment during the first month of each pregnancy (Guberan et al, 1994). In an analysis of 1781 pregnancies, neither category of exposure was associated with an unusual sex ratio. Nor was the use of short-wave equipment associated with a higher prevalence of low birthweight (under 2500 g). Data on work with microwave equipment and low birthweight were not reported.

42 As part of a case–control study of cardiovascular malformations in Finland, occupational exposure to microwave ovens was ascertained by interviewing the mothers of 406 cases and 756 controls (randomly selected from all births) approximately three months after delivery (Tikkanen and Heinonen, 1992). Daily exposure during early pregnancy was reported by 2.7% of case mothers and 1.9% of controls. For occasional exposure the corresponding proportions were 3.4% and 2.5%. Neither of these differences was statistically significant.

43 In a Dutch case–control study, the parents of 306 mentally retarded children and 322 controls with other congenital handicaps for which the cause was known (eg familial disorders and cerebral palsy) were interviewed about exposures from three months before conception to six months after the child was born (response rate 89.5%) (Roeleveld et al, 1993). Associations were found with maternal occupational exposure to non-ionising radiation during the last three months of pregnancy (OR 9.3; 95% CI 1.5–55.7) and also earlier in pregnancy and before conception. There was also an increased risk with paternal exposure to microwaves or RF radiation before conception

(OR 2.5; 95% CI 1.1–5.7). However, the exact nature of these exposures is unclear. Many other exposures that were examined were also more common among the case parents, although generally with rather lower odds ratios. This suggests that risk estimates may have been inflated by recall bias.

44 A survey of personnel (mostly male) from the Royal Australian Air Force who had operated radar stations during World War 2 found an apparent excess of twin births (17 vs approximately 8 expected) (Flaherty, 1994). However, the sampling frame and the derivation of the expected number were not described, the possibility of response bias was not addressed, and no distinction was made between monozygotic and dizygotic twins.

45 A study in the USA explored the association of birth defects with paternal exposure to microwaves, short-wave therapy and other treatments used in physiotherapy (Logue et al, 1985). Matched cases (n = 169) and controls (2 per case) were identified from 3004 male physiotherapists who had answered a postal questionnaire about occupational exposures and the occurrence of various specified congenital anomalies in their children. The number of defects reported was high in comparison with rates from the National Center for Health Statistics, but there was no statistically significant association with exposure to non-ionising radiation at any time before conception or specifically in the three months before conception. The power of the analysis to detect such associations is unclear.

46 In addition to the epidemiological investigations of birth outcomes that have been summarised, two reports have described the use of microwave heating to relieve pain during labour (Daels, 1973, 1976). No adverse effects were noted in a series of 2000 patients treated in this way (Daels, 1976).

47 In five studies that were reviewed by the Advisory Group in 1994, the risk of congenital malformations did not appear to be increased among women who had used VDUs early in pregnancy (AGNIR, 1994). However, little information was available at that time on the relation of VDU use to other birth outcomes such as low birthweight, and no further studies on VDUs and birth outcome have been published more recently.

Conclusions

48 Several studies have reported an increased risk of congenital malformations following maternal occupational exposure to RF radiation during pregnancy, principally in physiotherapy. However, the observed associations have not related consistently to any single category of malformation, and may have resulted, at least in part, from recall bias (because case mothers were more motivated to remember potentially noxious exposures than controls). The current balance of epidemiological evidence does not indicate an effect of paternal exposure to RF radiation on the risk of birth defects. Nor does it consistently suggest an effect of such exposure, either in mothers or in fathers, on other birth outcomes.

FUNCTIONAL NEUROLOGICAL AND CARDIOVASCULAR DISORDERS

49 Reports from Eastern European countries and the USA have described functional disturbances of the nervous and cardiovascular systems in people working with microwave-generating equipment, and have proposed a syndrome known as 'microwave

sickness' (Michaelson, 1982; Hocking, 2001). The postulated clinical features include 'neurasthenic' symptoms such as headache, fatigue, irritability, loss of appetite, sleepiness, sweating, difficulties in concentration or memory, depression, emotional instability, and also bradycardia (or occasionally tachycardia), hypertension and abnormalities of cardiac conduction. These have been claimed to occur with exposures around a few tens of W m^{-2}. However, many of the studies focusing on illness of this type have lacked scientific rigour.

50 For example, during the 1950s, medical assessment of 226 employees who were exposed to microwave radiation at an airframe manufacturing company in the USA and 88 unexposed controls, found no evidence of pathology or adverse physiological effects that could be 'unequivocally' attributed to microwave exposure (Barron and Baraff, 1958). However, no formal statistical analysis was reported, and the power of the study to detect different categories of effect was unclear. In Poland, the occurrence of functional disorders of the nervous, gastrointestinal and cardiovascular systems among a cohort of 841 male microwave workers was unrelated to their level (2–60 W m^{-2} vs less than 2 W m^{-2}) or duration of exposure (Siekierzynski et al, 1974b), but diagnostic criteria were not specified, and potential confounding factors other than age were not taken into account. In contrast, a Russian survey of workers exposed to microwaves in the maintenance of radio equipment indicated a substantial excess of many symptoms and clinical abnormalities in comparison with unexposed controls (Sadcikova, 1974). Again, however, diagnostic criteria were not well specified, and it is unclear whether the method of eliciting data was comparable for exposed and control subjects.

51 As part of a study of 322 male radar workers in the former Yugoslavia who had been exposed to pulsed microwaves (generally less than 50 W m^{-2}) for five to ten years, a detailed clinical assessment was made, and the findings compared with those in 220 controls (Djordjevic et al, 1979). 'Neurocirculatory asthenia' was diagnosed in 15.5% of the radar workers and 13.2% of the comparison group, a difference that was not statistically significant. However, the exact diagnostic criteria were not specified. Moreover, it is unclear whether the doctors who examined the subjects were aware of their exposure status. Subsequently, the study was extended to include 500 radar operators and 350 controls (Djordjevic et al, 1983). No significant differences were observed in the frequency of neurosis, hypertension or hypotension.

52 A survey of personnel who had served in the American embassy in Moscow during 1953, some of whom had been exposed to a microwave beam directed at the embassy building, indicated a somewhat higher frequency of commonly reported symptoms (depression, irritability, difficulty in concentration and memory loss) than among controls from other Eastern European embassies (Pollack, 1979). However, within the Moscow group, the prevalence of these complaints was not related to microwave exposure. Maximum exposures were estimated to be 0.18 W m^{-2}.

53 An Italian survey of seven workers with prolonged occupational exposure to RF radiation in the wood industry found differences from fifteen controls in answers to questions about social relations and symptoms of anxiety (Antoniazzi et al, 1983). However, because of the small sample size and potential for uncontrolled confounding, little can be drawn from this finding.

54 A somewhat larger study, also in Italy, collected information from 63 women who worked in a factory where RF sealers were used in the production of plastic goods (Desideri et al, 1985). Of these women, 30 were classed as exposed to RF radiation, 11 as 'partially' exposed, and 22 as unexposed. Eye irritation and paraesthesiae of the upper limbs were more common in the exposed group.

55 In Sweden, 51 men and 62 women who had been exposed to RF radiation for more than five years through work with plastic welding machines were interviewed about symptoms and underwent tests of two-point discrimination in the fingers (Kolmodin-Hedman et al, 1988). The prevalence of neurasthenic symptoms was approximately 20% as compared with an expected rate of 9%. The latter figure was apparently derived from national reference data, although details of the method are lacking. For the women, it was also possible to compare findings with those in 23 unexposed sewing machine operators. No important differences were found in the prevalence of muscular pain (58% vs 62%) or tiredness (60% in both groups), and headache was less common than in the controls (42% vs 52%). However, more of the exposed women reported numbness and paraesthesiae (53% vs 22%), and two-point discrimination was abnormal in more than a third of exposed women as compared with only 1 of 23 controls. Furthermore, there was a dose–response relation between measured exposures and impaired two-point discrimination. The exact procedure for assessing two-point discrimination is not reported (it was done using dividers), and it is possible that bias might have occurred in the measurement, especially if the observer was not blind to the subject's exposure.

56 A radio location station in Skrunda, Latvia, was found to produce a mean power density of 3.205 mW m^{-2} at a distance of 3.7 km with a peak power about 50 times higher (Kolodynski and Kolodynska, 1996). To look for possible adverse effects of exposure, neuropsychological tests were carried out in 224 children aged 9–18 years who lived locally, 385 who lived elsewhere in the same region, and 357 from another region. The participants were reported to come from similar social backgrounds. After allowance for age (in two-year strata) and sex, the exposed children had poorer short-term memory, attention and (in girls) motor reactions than the other two groups. The differences that were observed between the groups were relatively large, but the possibility of unrecognised confounding (eg relating to nutrition, educational provision or general health) and of observer or reporting bias cannot be excluded.

57 A postal survey of 530 men and women in France found a raised prevalence of reported tiredness, headache, sleep disturbance, irritability, depression, loss of memory, dizziness and reduced libido among those living close to mobile phone base stations (Santini et al, 2002). However, the exact method by which subjects were selected for study and the response rates achieved are unclear. Moreover, residential proximity to base stations was ascertained through the questionnaire and was not independently verified. Thus, there may have been major bias, both in the recruitment of participants and in the information that they provided.

58 In Singapore, where mainly GSM phones were used, a sample of 808 people aged 12–70 years were interviewed about various symptoms, and about their use of mobile phones (Chia et al, 2000). Report of headache was associated with the use of handheld phones (prevalence ratio, PR 1.31; 95% CI 1.00–1.70 in comparison with non-users), and risk increased with the duration per day of such use. In contrast,

headache was inversely related to the daily duration of using hands-free phones. No significant differences were found between users and non-users of handheld phones in the prevalence of visual disturbance (9.3% vs 11.0%), facial tingling (3.9% vs 2.1%), facial burning (4.5% vs 4.0%), ear burning (2.5% vs 1.9%), sense of warmth behind the ear (7.0% vs 6.6%), unusual tiredness (16.6% vs 20.2%), loss of memory (15.5% vs 18.1%), difficulty in concentration (14.9% vs 20.9%), or dizziness (30.1% vs 30.5%).

59 The relation of headache and other symptoms to use of mobile phones was also examined in a large cross-sectional survey in Sweden and Norway (Sandström et al, 2001). Subjects were selected at random from the registers of a phone operating company, and were asked to complete a postal questionnaire about the types of mobile phone used, the extent of usage, various potential confounding factors (eg age, sex, occupation and psychosocial variables) and whether symptoms had occurred at least once a week over the past year. Response rates for questionnaires that were correctly addressed were 66% in Sweden and 58% in Norway, and after exclusion of responders who used more than one phone, the analysis was based on 4250 subjects from Sweden and 1872 from Norway. In both countries, the participants were predominantly male. For both analogue and digital phones, weekly duration of calls was positively related to sensations of ear warming, fatigue, headaches and burning skin. In addition, ear warming was more common in users of analogue as compared with digital phones. Subsequent investigation of a subset of 2402 participants who used any of the four most common GSM mobile phones suggested that the prevalence of some symptoms (but not of memory loss or fatigue) was higher when specific (energy) absorption rates (SAR values) were larger, especially if phones were used for a long time per day (Wilen et al, 2003).

60 As discussed in Chapter 5, a neuropsychological investigation in Hong Kong found that children who were regular users of mobile phones performed significantly better than controls who did not use them in several tests of attention (Lee et al, 2001). However, this difference could reflect characteristics of the type of people who are likely to use mobile phones, and does not necessarily indicate an effect of phone usage on neurological function. (For further discussion of this paper see Chapter 5, paragraph 27.)

61 In a survey of 161 students and workers at a French engineering school, difficulty in concentration was reported significantly more often by users of 1800 MHz DCS cellular phones than of 900 MHz GSM phones (Santini et al, 2001).

Conclusions

62 Some studies, particularly in Eastern Europe and Scandinavia, have suggested a marked excess of 'neurasthenic symptoms' in people exposed to RF radiation through work or use of mobile phones. However, this has not been a universal finding. In some investigations, associations may have occurred spuriously as a consequence of biased ascertainment of health outcomes or failure to take adequate account of confounding variables. In addition, the apparent inconsistency of findings from one country to another raises the possibility that the occurrence of such symptoms is psychologically induced and determined by cultural influences and health beliefs rather than a direct effect of RF radiation.

SYMPTOMS WHEN MOBILE PHONES ARE USED

63 A number of reports have described the occurrence of symptoms in close temporal relation to the use of mobile phones. In Australia, Hocking interviewed 40 volunteers who had responded to a notice in a medical journal, seeking individuals who had experienced symptoms in this way (Hocking, 1998a). The most common complaints were pain, dysaesthesiae and a warm sensation in the head, especially the temple, that in some cases radiated to the jaw, neck, shoulders or arm. In most subjects the symptoms started within five minutes of beginning a call, but 12 people said that the sensation built up gradually as the day progressed. In 19, the problem ceased within an hour of stopping calls. One had only developed symptoms after changing to a digital phone.

64 Later, Hocking and Westerman reported a further case in which a man developed permanent unilateral dysaesthesiae of the scalp after prolonged use of a mobile phone with associated abnormalities on current perception threshold testing of the cervical and trigeminal nerves (Hocking and Westerman, 2000). In another patient, who complained of localised scalp symptoms when she used a mobile phone, current perception thresholds in the affected area increased markedly following a provocation test in which she spoke into a phone (wrapped in thin polystyrene to avoid heating effects) for seven minutes (Hocking and Westerman, 2002).

65 A survey of 161 students and workers at a French engineering school asked about four symptoms at the time of using mobile phones (Santini et al, 2001). The two most frequent complaints were warming of the ear and unspecified discomfort.

66 Concerns have also been expressed that use of mobile phones may lead to an acute rise in blood pressure, and two cases of stroke have been reported in young women while making calls (Hocking, 1998b).

67 Various mechanisms might account for the occurrence of symptoms when mobile phones are being used. Frey has pointed out that headaches were also reported in relation to exposure to low intensity microwaves during research on microwave hearing, and has speculated that they could be produced by interference with the blood–brain barrier (Frey, 1998). It is also possible that sensations of warmth in and around the ear are caused directly by microwave irradiation from the antenna of the phone, although conduction of heat from the handset might also be responsible. Another possibility is that symptoms are triggered or exaggerated by psychological mechanisms. In support of this, when 20 subjects who considered themselves sensitive to mobile phones were exposed blind to radiation from mobile phones, the incidence of symptoms was lower than during periods of sham exposure (Hietanen et al, 2002). This is a strong design to distinguish whether symptoms are due to RF exposure.

68 In another study (Zwamborn et al, 2003), described in more detail in Chapter 5, blinded experimental exposure to electromagnetic fields similar to those produced by a UMTS base station antenna, with a peak field strength of 1 V m^{-1}, was associated with a significant reduction in 'well-being' (assessed by a questionnaire) in 36 individuals who had previously registered symptoms which they attributed to antennas. Moreover, a significant reduction in well-being was also observed in a group of 36 healthy volunteers when similarly exposed. However, there was no significant effect on well-being from exposure of the symptomatic subjects to 900 or 1800 MHz GSM-type fields,

as might have been expected had their symptoms genuinely been attributable to a noxious effect of such radiation.

69 Psychological mechanisms could also explain a rise in blood pressure during use of mobile phones. Thus, in the study by Hietanen et al (2002) described earlier, heart rate and systolic blood pressure both tended to be higher with sham than real exposures. Against this, another placebo-controlled and blinded experiment (in this case involving healthy volunteers who had not been selected on the basis of symptoms) found a significant increase in systolic blood pressure with exposure to radiation from a 900 MHz GSM mobile phone (Braune et al, 1998). However, a later study by the same principal author failed to confirm the finding (Braune et al, 2002). Exposure to a GSM-like signal (900 MHz pulsed at 217 Hz) for 50-minute periods from a mobile phone mounted on the side of the head had no statistically significant effect on blood pressure, heart rate or serum levels of adrenaline, noradrenaline and endothelin.

Conclusions

70 It is clear that some individuals report symptoms (most commonly of hotness or altered sensation over the ear and adjacent parts of the scalp) when they use mobile phones. It is possible that localised heating occurs as a consequence of radiation from the phone's antenna or through conduction from the handset. The mechanism underlying symptoms and associated clinical abnormalities is uncertain, but in some cases, at least, could be psychological.

HAEMATOLOGICAL ABNORMALITIES

71 A report in 1943 described the results of periodic health surveillance in 45 men who had been exposed to radar and high frequency RF radiation for between two months and nine years (Daily, 1943). Findings from blood examinations were considered to fall within the normal range.

72 Blood counts were also carried out as part of a programme of physical examinations for personnel exposed to radar in the manufacture of airframes in the USA (Barron et al, 1955). Among 226 workers exposed for up to four hours per day over a period of up to thirteen years, total counts of red and white blood cells were unremarkable. However, 25% had a low proportion of polymorphonuclear leucocytes (< 55%) as compared with only 12% of 88 unexposed controls.

73 Prompted by the observation of several cases of polycythaemia in patients who had been exposed to radar, an American military physician carried out a small case–control study (Friedman, 1981). By searching the records of a blood bank, he identified 14 male patients who had been referred for treatment of polycythaemia over the previous five years. When interviewed by telephone, seven of the men gave strong histories of chronic exposure to microwaves. In contrast, no chronic exposure to microwaves was reported by 17 consecutive age-matched controls who came to the same laboratory for blood tests because of disorders other than polycythaemia. It is unclear from the report whether the study included any of the cases that initially raised suspicions, whether the controls came from the same catchment population as the cases, and what steps, if any, were taken to minimise bias in the ascertainment of exposures. Nor was the level of exposures described.

74 A study in the former Yugoslavia compared fourteen men who had been occupationally exposed to pulsed microwaves for seven to fourteen years (generally at less than 50 W m^{-2}, but occasionally at up to four times this level) and ten unexposed controls (Goldoni, 1990). Haematological examinations were carried out on two occasions at an interval of two years, and at the second examination the exposed men had a significant reduction in thrombocyte and leucocyte counts, and significantly lower erythrocyte and leucocyte counts than the controls. It is unclear how measurements in the exposed and control groups compared at the time of the first examination.

75 In contrast, no significant differences were observed in haematological parameters in another Yugoslavian study which compared 500 radar operators and 350 controls matched for age and social conditions (Djordjevic et al, 1983).

Conclusions

76 Reported haematological abnormalities in workers exposed to RF radiation have generally been minor, as well as being inconsistent between studies. The findings do not suggest a hazard.

OTHER MORBIDITY

77 A large retrospective cohort study compared two groups of US Navy personnel – approximately 20 000 men with high opportunity for exposure to radar, and a similar number with low potential for such exposure (Robinette et al, 1980). In the first group, some peak exposures may have exceeded 100 W m^{-2}, but mean exposures were much lower than this. Rates of admission to Navy hospitals over an aggregate period of seven years were significantly different in the two groups for two of eighteen diagnostic categories analysed, but in both cases it was the men with low exposure who had the higher rate. Similarly, admissions to US Veterans Administration hospitals and compensation for disability tended to be more common in the low exposure group.

78 In a postal survey of male physiotherapists in the USA, questionnaires about health and work were returned by 3004 men, a 58% response rate (Hamburger et al, 1983). The researchers explored associations between a range of illnesses and the use of four treatment modalities – ultrasound, infrared, microwave and short-wave diathermy. The only statistically significant finding was an excess of heart disease in relation to use of short-wave treatments.

79 A case of mediastinal fibrosis has been reported in a man who had worked for 18 years at a military radar base with exposures to microwave radiation that may have exceeded 10 W m^{-2} (Papandreou et al, 1992). However, no other examples have been published of this unusual combination of exposure and disease, which may simply have occurred by chance. It has been pointed out that the absorbed power density in the mediastinum where the fibrosis occurred would have been extremely low (a few nanowatts per gram of tissue) (Hocking and Joyner, 1993).

80 Studies principally in Sweden, but also in other countries, have indicated an increased frequency of rashes and symptoms such as itching, burning and stinging of the skin in association with the use of VDUs (AGNIR, 1994). At that time, the Advisory Group concluded that the effect was not caused by electromagnetic fields, but might be mediated through electrostatic fields in conditions of low humidity. More recent

research tends to support this view. Thus, although one Swedish case–control study found an association between skin symptoms in office workers and exposure to VDU-related electromagnetic fields (Stenberg et al, 1995), no relation to electric or magnetic fields was observed in another survey (Bergqvist and Wahlberg, 1994). While one double-blind intervention study suggested that facial skin complaints in VDU users could be reduced by anti-static measures (Skulberg et al, 2001), no such benefits were observed in two other studies from reductions in low frequency VDU electromagnetic fields (Oftedal et al, 1999; Lonne-Rahm et al, 2000).

81 In Japan, Kimata compared the allergic responses of 26 adults with atopic eczema before and after real or sham exposure to RF radiation for 60 minutes from a mobile phone tied round the neck (Kimata, 2002). Wheal responses to skin prick testing with house dust mite and Japanese cedar pollen increased significantly following real exposure, as did plasma concentrations of substance-P and vasoactive intestinal pesticide. No such changes were observed with sham exposure. However, the absence of similar findings in a study of 20 patients with allergic rhinitis (Kimata, 2002) suggests that the change in immune parameters may have occurred by chance or through unrecognised confounding. It is of note that all subjects were tested simultaneously, first with the real exposure, and then, one week later, with the sham exposure.

Conclusions

82 Clinical and epidemiological data do not suggest an effect of RF radiation on the other health outcomes considered in this section.

SUMMARY

83 RF radiation can cause thermal injury to tissues, but such effects have only been reported from exposures above the current guideline levels for the UK. Pulse modulated RF fields can give rise to audible buzzing or clicking sounds, which are produced through thermoelastic expansion of soft tissues in the head. These noises could be annoying, but would not be expected to cause any long-term adverse effect on health. Some studies have suggested that exposure to microwave radiation can lead to minor defects in the posterior pole of the lens of the eye, but this has not been a consistent finding, and there is no indication that any form of RF radiation has caused clinically important cataracts in exposed people.

84 Three out of five published studies have suggested a reduction in sperm counts in workers exposed to RF radiation, but all of these studies were small and one was of doubtful rigour. Few epidemiological data are available on the relation of RF radiation to female fertility, and the findings are inconclusive. RF radiation does not appear to induce spontaneous abortion in women who are exposed during pregnancy, but a small effect on risk cannot be excluded. Although several studies have suggested that RF exposure of mothers is associated with an increased frequency of birth defects, the associations have not related consistently to any one class of malformation, and may reflect biases in the ascertainment of exposures. The current balance of evidence does not indicate an effect of paternal exposure to RF radiation on the risk of congenital malformations. Nor is there consistent evidence that exposure of either mothers or fathers is related to other birth outcomes.

85 Studies in Eastern Europe and Scandinavia have demonstrated a marked increase in the prevalence of reported neurasthenic symptoms among people exposed to RF radiation, but this finding has been inconsistent from country to country and in an experiment where people who considered themselves to be sensitive were exposed blind to RF radiation from mobile phones, they did not report more symptoms from actual than from sham exposure. It is possible, therefore, that the symptoms are determined by cultural influences and health beliefs, and do not result from a direct, toxic effect of RF radiation. Some individuals experience hotness or altered sensation over the ear or adjacent parts of the scalp when using a mobile phone. This may result from localised heating, generated either by radiation from the phone's antenna or by conduction of heat from the handset. In addition, psychological mechanisms may again have a role.

86 Reported haematological abnormalities in workers exposed to RF radiation have been minor and inconsistent, and do not suggest a hazard.

87 Clinical and epidemiological studies do not suggest an adverse effect of RF radiation on other, non-cancer health outcomes.

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7 Epidemiological Studies of Radiofrequency Field Exposure and Cancer

1 Epidemiological studies of the relation of radiofrequency (RF) field exposure to risk of cancer can be divided broadly into studies of

(a) users of cellular (mobile) phones,
(b) persons with potential occupational or hobby exposures to RF fields,
(c) populations who might have exposure from living near RF transmitter masts – so far these have related to TV and radio, not mobile phone, masts.

For (b) and (c), ie occupational and residential exposures, this chapter summarises briefly the literature covered in the IEGMP (2000) report, and goes into detail only on the papers published subsequently. For (a), ie mobile phones, however, all studies have been reviewed in detail, because of the particular public interest in this exposure.

MOBILE PHONES

2 The possible relation of mobile phone exposure to risk of cancer has been addressed by both case–control studies (ie studies comparing phone use in 'cases' – patients who have had the cancer under study – with use in 'controls' – individuals who have not had this cancer) and cohort studies (ie studies following-up risks of cancer over time in individuals classified according to their history of phone use). With one exception (Auvinen et al, 2002), the information on exposures in the case–control studies has come from recall by the subjects at interview, whereas in the cohort studies it has come from billing records. The strengths and weaknesses of the studies reflect their designs and data sources, and therefore studies of these different design types are discussed separately below.

Case–control studies

3 Five case–control studies have been published on the relation of mobile phone use to risk of brain tumour, two from Sweden, two from the USA, and one from Finland. They are summarised in Table 7.1. Several of the brain tumour studies published some results separately on acoustic neuromas. In addition, a small study in the USA published data on acoustic neuromas but not other brain tumours (Warren et al, 2003). There have also been single case–control studies of salivary gland tumour, uveal melanoma, testicular cancer and intratemporal facial nerve tumour, which are discussed later.

Brain tumour: Hardell et al, 1999a,b, 2000, 2001

4 The first case–control study to be published, by Hardell et al (1999a), included people with histologically verified benign or malignant brain tumours, including acoustic neuromas, incident in the Uppsala-Orebro region of Sweden in 1994–96, and in the Stockholm region in 1995–96, who were aged 20–80 years at the time of diagnosis. A total of 209 cases were included, which the authors stated was a 90% response rate; this rate is doubtful, however, for the reasons discussed below. Two controls per case were

chosen from a population register, with matching on sex, age and region, of whom 425 responded and were included in the analyses. This was stated to be a 91% response rate. It was stated that the analysis was matched, but it was not explained how this was done when controls must have been included who had originally been matched to cases who were not in the analysis (as 425 is more than twice 209). Information about mobile phone use was obtained by a postal questionnaire, which was supplemented by a telephone interview for clarification if answers were unclear and also to confirm mobile phone use if this was reported to have occurred; the clarification was stated to have been conducted blind to case–control status. Phone use within the year before tumour diagnosis was disregarded. There was no validation of phone use against records.

5 The study found no raised risk of brain tumour in relation to phone use overall (odds ratio, OR, 0.98; 95% confidence interval, CI, 0.69–1.41), no raised risk for digital or analogue exposures separately, and no relation of risk to cumulative duration of use or use several years earlier. The abstract of the publication emphasised an increase in risk of occipital or temporal (including temporoparietal) tumours on the same side as the reported phone use, present for phone use overall and for use of analogue but not digital phones. This increase was not statistically significant, however, and it is not plausible to interpret it as aetiological because it occurred in the context of no overall raised risk in phone users (ie presumably it was accompanied by a counterbalancing reduced risk for contralateral tumours).

6 In subsequent multivariate analyses incorporating non-phone variables significantly related to brain tumour risk in the study (medical x-rays of the head and neck, and laboratory work) the risk of temporal, occipital and temporoparietal tumours combined in ipsilaterally phone-exposed subjects was just significantly raised (OR 2.62; 95% CI 1.02–6.71) (Hardell et al, 2000)*. The odds ratio for tumours of these sites in subjects who had used phones on both sides was 0.71 (95% CI 0.14–3.68). The authors noted that it was unlikely that there was reporting bias varying by the anatomical site of the tumour. It remains a possibility, however, that there was reporting bias regarding whether subjects stated their phone use was ipsilateral, contralateral or both, given that subjects will have known the side of their tumour.

7 The methods and presentation of this study have been strongly criticised (Ahlbom and Feychting, 1999; Boice and McLaughlin, 2002).

8 For several reasons the response rate of cases reported by Hardell et al (90%) appears likely to be seriously inflated by conventional standards. The authors reported that to be eligible in their view, cases had to be alive at the start of their study, whereas conventional response rates would be calculated in relation to patients who had tumours incident during the study period, whether or not they had died before the start of data collection. The number of individuals lost in this way was not stated in the paper. The study was also restricted to cases with a histopathological diagnosis available at the time of operation according to the cancer registry (Hardell et al, 2000). Furthermore, within the subjects who were eligible according to the authors' criteria, 37 were too ill to participate and these too, unconventionally, were excluded when calculating the response rate.

* The results were published again, with a little extra detail and rephrasing of some of the sentences in the text, in a further paper (Hardell et al, 2001).

TABLE 7.1 *Case–control studies of mobile phone use and risk of brain tumours*

Study	Country	Number of cases	Number of controls	Ages at diagnosis (years)	Source of controls	Prevalence of ever use * in controls	Odds ratio (95% CI), ever use *	Phone type
Hardell et al, 1999a	Sweden	209 †	425	20–80	Population register	38%	1.0 (0.7–1.4)	Mainly analogue, 450 or 900 MHz
Muscat et al, 2000	USA	469 ‡	422	18–80	Hospital IP, malignant and non-malignant conditions	18%	0.8 (0.6–1.2)	Mainly analogue 800–900 MHz
Inskip et al, 2001	USA	782 †	799	≥18	Hospital IP, non-malignant conditions	29%	0.9 (0.7–1.1)	Mainly analogue 800–900 MHz
Auvinen et al, 2002	Finland	398 ‡	1986	20–69	National population register	11%	1.3 (0.9–1.8)	Slightly more analogue than digital
Hardell et al, 2002a	Sweden	1303 †	1303	20–80	Population register	15% analogue § 30% digital §	1.3 (1.0–1.6) § 1.0 (0.8–1.2) §	Analogue 450 or 900 MHz Digital 1900 MHz

* The meaning of 'ever use' varied between studies: 8+ hours of use in Hardell et al (1999a); ever had a subscription in Muscat et al; use more than five times in Inskip et al; record of ever having had a personal subscription in Auvinen et al; any use more than one year before brain tumour (or comparable period for control) in Hardell et al (2002a).
† Including acoustic neuroma.
‡ Not including acoustic neuroma. Muscat et al (2002) published a separate paper on acoustic neuroma – 90 cases and 86 controls.
§ Analyses not published for mobile phones overall.

TABLE 7.2 *Cohort studies of mobile phone use and risk of cancer*

Study	Country	Number in cohort	Age (years)	Person-years of follow-up	Endpoint	Number of cancer deaths/cases	Phone type	Relative risk (95% CI) brain and NS tumours	Relative risk (95% CI) leukaemia
Dreyer et al, 1999	USA	285 561	≥20	285 561 *	Mortality	95	Analogue	–†	–†
Johansen et al, 2002a	Denmark	420 095	≥18	1 128 493	Cancer incidence	3391	Analogue (450 or 900 MHz) or digital (GSM) ‡	1.0 (0.8–1.1)	1.0 (0.8–1.2)

* Number obtained by summing person-years by category of user reported in the paper. As there was one year of follow-up of 285 561 people, with deaths occurring, the person-years would be expected to be slightly lower.
† Relative risks not published. For brain tumours, standardised mortality rates per 100 000 person-years were 2.0 for non-handheld, 3.7 for low use per day handheld, and 0 for higher use handheld. For leukaemia the rates for these groups were 7.0, 1.6 and 4.9, respectively.
‡ 58% were digital at first subscription, but average follow-up was longer for analogue than digital users.

9 These problems are minor, however, compared with a consideration of the apparent response rate in relation to the number of cases incident during the period. Ahlbom and Feychting (1999) noted that the cancer registry had recorded 862 cases that met the study criteria on age, region of residence and date of incidence. As survival was 77% at six months and 65% at one year, mortality could not account for most of the shortfall between this and the 209 cases actually interviewed. As Ahlbom and Feychting delicately noted 'there appears to be an inconsistency between the actual study and the way it was reported in the article'*. If the response rate was anything like the 203/862, ie less than 25%, implied by Ahlbom and Feychting in their letter, there would be considerable potential for selection bias, but also for disquiet about the way in which the study has been reported and whether other aspects of the study had similarly been reported in an unsatisfactory manner.

Brain tumour: Muscat et al, 2000 and 2002

10 The next case–control study was by Muscat et al (2000) from the USA. It included 469 cases and 422 controls matched on age, sex, race and month of admission.

11 Forty-three of the interviews for cases and six for controls were with proxies rather than with the subjects themselves. The controls were patients from the same hospitals as the cases, who at some hospitals had a benign condition and at others were mainly patients with malignancy, excluding leukaemias and lymphomas. Information about mobile phone use was obtained by questionnaires to the subjects. These questionnaires also collected information about several potential confounders, although ionising radiation was not specifically mentioned among these. The response rate for cases was 70% and for controls was 90%. Fourteen per cent of cases and 18% of controls had used (handheld) mobile phones†. A smaller proportion of controls with malignancy (6.1%) than of other controls had ever used mobile phones, but this was largely because patients with malignancy were older.

12 No raised risk was found for ever regular-use of handheld mobile phones, or for frequency of use, and there was no association with cumulative duration of use. There were no significant risks for any specific histologies of brain tumour. There was no indication of a trend in risk with number of years of use of phones, number of hours per month of use or number of cumulative hours of use, and no case–control difference in the proportion of subjects who had used digital phones. Relative risks were 1.1 or less for each anatomical site of brain tumour. Among users, there was a nearly significant excess of tumours ipsilateral to the side of phone use for cerebral tumours overall ($p = 0.06$) but no ipsilateral excess for temporal lobe tumours.

* Hardell et al replied to this criticism (Hardell et al, 1999b) without giving any indication of the correct figure. Subsequently they stated (Hardell et al, 2002a) that 565 of the cases were eligible (which would give a response rate of 36%), and implied that the registry data had major problems with incorrect diagnoses – this would not accord with the reputed quality of Swedish cancer registration. Confusingly, in a letter (Hardell et al, 1999b) and in a footnote in the 2002 paper Hardell et al stated, contrary to the original 1999 publication, that benign tumours were only intended to be included for part of the period in one region; again, the reporting of the study is unsatisfactory.

† Here and subsequently, where results are described for phones without specification of whether they are digital or analogue, it is because they were so presented in the original paper: the mix of digital vs analogue use in each study population is stated in Tables 7.1 and 7.2.

13 In addition to the analyses for brain tumours, Muscat et al (2002) also published data on risks of acoustic neuroma in relation to mobile phone use. Using the same design of study and matching as described above, 90 acoustic neuroma cases were compared with 86 controls admitted to the same hospitals with non-malignant conditions. All but one of the subjects underwent personal rather than proxy interviews. A slightly lower percentage of cases (20%) than of controls (27%) reported regular use of mobile phones. There was no trend in risk of acoustic neuroma in relation to number of years of phone use, hours per month of use, or total hours of use, and there was reported to be no significant relation between side of phone use and side of tumour (although the results presented in the paper appear to have a typographical error*).

Brain tumour: Inskip et al, 2001

14 The third study was that by Inskip et al (2001) from the USA, which obtained data from 782 cases, who were subjects aged 18 years and older with brain tumours, malignant or benign, treated at the participating hospitals and living within 50 miles of them; 92% of eligible subjects agreed to take part. Data were also obtained from 799 controls aged 18 years and older who had been admitted to the same hospitals as the cases with non-malignant conditions, mainly accidents, cardiovascular disease and musculoskeletal disease, frequency matched to the cases on hospital, age, sex, race, and proximity of residence to hospital. Of eligible controls contacted, 86% participated in the study. Exposure data were obtained by interview by a research nurse, with proxy interviews undertaken for patients who were too ill or had died – namely, 16% of patients with glioma, 8% of those with meningioma, 3% of those with acoustic neuroma and 3% of controls. The analyses were conducted with adjustment for several potentially confounding variables.

15 Use of handheld phones was less common (22%) among controls with circulatory diseases than among other controls, but this was explicable by their older age. Cumulative use of mobile phones for 100 hours or more compared with never or rare use gave a relative risk of brain tumour of 1.0, and there were not significantly raised risks for any histology. There was no relation of risk of brain tumour to duration (years) of use of phones, amount of use per day, total cumulative hours of use, or use in early years, either for brain tumours overall or for the major histological groups of tumours, and there were no significant risks in subdivisions of glioma by histology, grade, laterality or lobe of the brain. Among subjects who had used phones regularly for at least six months before diagnosis, laterality of tumour was not significantly related to reported laterality of phone use. The study results related mainly to use of analogue phones.

Brain tumour and salivary gland cancers: Auvinen et al, 2002

16 Auvinen et al (2002) conducted a case–control study in Finland based on records of phone use. They identified from the National Cancer Registry all brain tumours (398) and salivary gland cancers (34) diagnosed at ages 20–69 years in Finland in 1996, and selected five age- and sex-matched controls per case from the national population

* The relative risk and p value presented do not appear to be compatible with each other (the relative risk appears to be incorrect), and are identical to those presented in the abstract as the values for risk in relation to phone use overall.

register. Four of these potential controls needed to be excluded because of a previous brain tumour. The authors used record linkage to obtain phone subscription histories for the cases and controls from the two network providers in Finland in 1996. This linkage only enabled identification of users who were the named subscriber for the phone and not, for instance, subjects who used a phone provided by their employer. Analogue 'bag' phones operating at 450 Hz were excluded from the analyses. Information on place of residence of the study subjects was obtained from the population registry of Finland and on occupation and socioeconomic status from the 1990, 1993 and 1995 censuses. Information on prior radiotherapy to the head and neck was obtained from the National Cancer Registry; this exposure was reported for three brain tumour cases and four controls.

17 In total, 13% of brain tumour cases, 12% of salivary tumour cases and 11% of controls had ever had a personal subscription for a mobile phone. The average duration of subscription was two to three years for analogue phones and less than one year for digital. The odds ratio for brain tumour for ever-subscription for a phone was 1.3 (95% CI 0.9–1.8) and for salivary gland tumour was also 1.3 (95% CI 0.4–4.7). The odds ratio for glioma was borderline significant [1.5 (95% CI 1.0–2.4)] and for other brain tumour histologies close to 1.0. Gliomas showed a significant relationship to use of analogue phones (OR 2.1; 95% CI 1.3–3.4) but not digital phones (OR 1.0; 95% CI 0.5–2.0). A significant trend in risk of glioma was found with duration of analogue subscription, but this did not occur in analyses confined to ever users. There was no trend in risk of glioma with duration of use of digital phones, and no significant relation of risk of meningioma or salivary gland tumour to duration of phone use. The results for brain tumours were not appreciably altered by adjustment for place of residence, occupation and socio-economic status.

18 The investigators had no information about the frequency or duration of calls or about the use of mobile phones provided by an employer, and they noted that in the study period there were more corporate than private subscriptions in Finland*. They stated, however, that 50% sensitivity in exposure assessment (if unbiased) would only have attenuated any real effects by 10%. There were no substantial differences in distribution of histology, affected lobe of the brain or laterality between gliomas occurring in phone users (32 cases) and gliomas occurring in age- and sex-matched subjects who had not been phone users.

Brain tumour: Hardell et al, 2002a,b and 2003a

19 Hardell et al (2002a), in their second case–control study on brain tumour aetiology, collected data from four regions of Sweden on brain tumours incident at ages 20–80 years during 1997 to mid-2000. The design was the same as in the authors' previous study. The cancer registry reported 2561 eligible cases, of whom 304 were considered by Hardell et al to be ineligible because they did not have primary brain tumours (232) or lived outside the study area (14) or their recorded year of incidence was incorrect (58). A total of 1617 cases were mailed, of whom 1429 answered the questionnaire, as did 1470 (91%) of 1617 controls invited to take part. Assistance in

* Perhaps it is for this reason that the prevalence of ever-subscription and of long-term subscription in the study are lower than might be expected from a country which was one of the earliest in Europe to have widespread use of mobile phones.

completing the questionnaire was given by relatives for 32.8% of cases and 9.5% of controls for whom this was known. The analyses were generally conducted for 1303 matched case–control pairs (Hardell et al, 2002a), although also some were unmatched (Hardell et al, 2003a).

20 The methods, analysis and presentation of the study have been heavily criticised (Boice and McLaughlin, 2002).

21 As in the previous study by Hardell et al, the presentation of the paper is not entirely satisfactory. The abstract (Hardell et al, 2002a) states that the study included 1617 patients, and later mentions 1429, but it does not mention 1303 – the number actually included in the analyses. The abstract claims an 88% response rate among cases, but the actual rate, conventionally calculated, appears to be 63% or less*.

22 Phone use more than a year before tumour diagnosis (or an equivalent period for the controls) gave relative risks of 1.3 (95% CI 1.02–1.6) for analogue phones, 1.0 (95% CI 0.8–1.2) for digital phones, and 1.0 (95% CI 0.8–1.2) for cordless phones (Hardell et al, 2002a). The relative risk for analogue phone use increased with induction period: relative risks were 1.4 (95% CI 1.04–1.8) for use more than five years earlier, and 1.8 (95% CI 1.1–2.9) for use more than ten years earlier. There was no evidence of such a trend for digital phone use, but for cordless phones relative risks of 1.3 (95% CI 0.99–1.8) and 2.0 (95% CI 0.5–8.0) were found for use more than five and more than ten years earlier, respectively†. In a multivariate analysis of the three phone types (but apparently not including potentially confounding non-phone variables), the relation of risk to induction period was no longer present for analogue phones but remained for cordless phones. There was no convincing or consistent evidence of greater risk in relation to greater cumulative hours of use of phones‡. An analysis of brain tumour risk in relation to duration (years) of use analysed as a continuous variable showed a significant trend in risk for analogue (OR 1.04; 95% CI 1.01–1.08) but not digital or cordless phones (Hardell et al, 2003a), with a significant risk also for acoustic neuroma in relation to analogue phone use. Such a result in an analysis that appears to have included the zero-use group, however, could occur even if there was no increase in risk in longer-term compared with shorter-term users; no categorised data were provided to enable this to be examined. Relative risks in users of 450 MHz, 900 MHz, and in subjects using both frequencies of analogue phones were, respectively, 1.0 (95% CI 0.7–1.4), 1.4 (95% CI 1.03–1.8) and 1.7 (95% CI 0.9–3.3) (Hardell et al, 2002a).

23 Anatomical localisation of the tumours by neuroradiology was available for the great majority of cases. In analogue phone users risk of temporal tumours was significantly raised (OR 2.0; 95% CI 1.3–3.1), but risks were not appreciably raised for other areas of the brain, including overlap areas (eg temporoparietal). Risks of temporal tumours were not raised for digital or cordless phone users.

24 For each type of phone, significant or borderline-significant raised risk was found for tumours in the brain hemisphere ipsilateral to the side of reported usual phone use

* Less if Swedish cancer registration is not really as inaccurate as Hardell et al claimed.

† In analyses restricted to malignant tumours, there was a suggestion of a greater risk with longer induction period for digital and cordless but not analogue phones (Hardell et al, 2002b).

‡ In analyses restricted to ipsilateral malignant tumours, there was an indication of a dose–response relationship only for cordless phones (Hardell et al, 2002b).

(ORs of 1.8, 1.3, 1.3 for analogue, digital and cordless phone use, respectively*). Similar results were obtained among individuals who had used only one of these phone types, and substantially greater ORs for ipsilateral than for contralateral use were present for each phone type for temporal and non-temporal tumours separately.

25 When risks were examined by histopathological type and phone type, the only significant risk was for acoustic neuroma in analogue phone users (OR 3.5; 95% CI 1.8–6.8). Risk in analogue phone users was also significantly raised for benign tumours overall, but was barely raised for malignant tumours. Similarly, risk in relation to analogue phones was not raised for malignant tumours in the temporal area, but was significantly raised for benign tumours in this area, most of which were acoustic neuromas (the risk for meningioma in the temporal area was nearly significantly raised (4.5; 95% CI 0.97–2.18), but based on small numbers). Essentially, about two-thirds of the raised risk of brain tumours in relation to analogue phone use, and almost all of the raised risk of temporal tumours in analogue phone users, was the consequence of the results for acoustic neuroma. There was no relation of acoustic neuroma risk to induction period, however (data were not presented in relation to duration of use). Some of the acoustic neuroma results were republished in Hardell et al (2003b), who also noted evidence of an increasing secular trend in incidence rates of acoustic neuroma in Sweden; this largely occurred in the early 1980s, however, well before the major increase in mobile phone use in Sweden.

26 The general direction of the results – greater risk for analogue than for other phone use, for longer than for shorter induction periods, and for temporal than for other sites of tumour – would accord with the pattern that would be expected if there were truly a long induction period, SAR-related effect of mobile phone use on cancer risk. The presence of a similar induction period effect for cordless as for analogue phones, however, argues for reporting bias, as the average power output of cordless phones is one to two orders lower than for analogue. There was also no relation to induction period for acoustic neuroma – the histology for which risk overall was significantly raised. The effect for analogue phones disappeared in a multivariate analysis, although this is difficult to interpret if cordless and digital phones are thought not to affect risk.

27 The results in relation to cumulative hours of use, although this is a crude measure of cumulative dose, do not support an aetiological relation. The results in relation to laterality of the tumour and laterality of phone use are suggestive of bias: the odds ratios for ipsilateral tumours were raised for all types of phone and for both temporal and non-temporal areas of the brain, while the odds ratios for contralateral tumours were below 1.00 in almost all instances.

Uveal melanoma: Stang et al, 2001

28 One case–control study has been published of mobile phone use and uveal melanoma in Germany (Stang et al, 2001). The study included 118 cases, of whom 37 were from a population-based study (84% response rate) and 81 from a single hospital (88% response rate). These cases were compared with 475 controls, matched on sex, age, and region of residence; 327 of these were from the population-based study,

* In analyses restricted to malignant tumours the corresponding ORs were 1.8, 1.6 and 1.5 (Hardell et al, 2002b) and in analyses by histology the ORs were significant for each phone type for astrocytoma on the same side as phone use (Hardell et al, 2003a).

chosen at random from a population register (48% response rate), and 148 were ocular disease patients from the hospital-based study, excluding occupational injuries to the eye (79% response rate). Exposure to mobile phones was assessed by interview (usually in person, sometimes by phone), but was restricted – unlike the studies discussed above – to occupational use. The screening question asked about use of mobile phones 'at your workplace for at least several hours per day'. This level of use 'ever' (which appears to mean for at least six months – the paper is not entirely clear) occurred 'certainly or probably' for 5.1% of cases and 3.2% of controls; this gave a significant relative risk of 4.2 (95% CI 1.2–14.5). 'Several', ie presumably two or more, hours per day is a very high level of use, and it seems surprising that 1 in 30 controls had such a high use solely from work, especially as most office or factory workers would presumably often use a fixed line rather than a mobile phone, and persons not in work would not have occupational use. The result derived largely from the hospital-based element of the study (OR 10.1; 95% CI 1.1–484.4). There were relative risks of four to five, although not significant, for use starting five or more years before diagnosis and use for three or more years. Cases were a little more often highly educated (twelve to thirteen years of schooling) or lowly educated (less than ten years of schooling) than controls, but analyses controlling for years of schooling (and analyses adjusting for iris and hair colour) did not alter the results. Mobile phones in Germany operated at 450–465, 890–960 and 1710–1800 MHz.

Acoustic neuroma and intratemporal facial nerve tumour: Warren et al, 2003

29 A case–control study in the USA (Warren et al, 2003) examined risks of acoustic neuroma and intratemporal facial nerve (IFN) tumours in relation to mobile phone use, on the stated grounds that the IFN would have high RF exposure levels from such phones and the acoustic nerve less so. The study only included 51 cases of acoustic neuroma and 18 of IFN tumour, however, and the subjects were from a tertiary care centre, not population-based. The controls were patients at the same hospital with certain non-cancer diagnoses, matched on age, sex and race.

30 The response rates of the cases and controls were not stated. Subjects were identified from a fiscal database at the hospital, and had to have been diagnosed over a stated period, but it is unclear how much later they were interviewed and how many died or lost contact in the interim. There were no significant risks of the study tumours in relation to mobile phone use (the risks for regular handheld mobile phone use were 0.4 (95% CI 0.1–2.1) for IFN and 1.0 (95% CI 0.4–2.2) for acoustic neuroma) or for various other RF exposures. Given the small numbers and the design deficiencies in the study, however, the results do not give substantial evidence.

Testicular cancer: Baumgart-Elms et al, 2002

31 A German case–control study compared occupational exposures from proximity to radio and mobile phones, and to radar, between 269 cases of testicular cancer, recruited on a population basis with a 76% participation rate, and 797 age- and region-matched controls, selected from population registers with a 57% participation rate (Baumgart-Elms et al, 2002). No increase in risk of the malignancy was found for men who reported ever working near mobile phones or radios (OR 0.9; 95% CI 0.6–1.2) or ever working near radar units (OR 1.0; 95% CI 0.6–1.7), or had a history of radar exposure as assessed

by experts from their occupational history (OR 0.4; 95% CI 0.1–1.2). Stratified analyses by blue/white collar, to adjust for socioeconomic confounding, did not show any substantially raised risks, and there was no trend of increasing risk with increase in a score representing duration of exposure and distance from the source, for men who had ever worked near mobile phones or radios, or near radar units. Thus the analyses do not suggest that RF exposures affect risk of testicular cancer.

Cohort studies

32 Results of two cohort studies have been published, one from the USA and the other from Denmark.

American cohort

33 The American study (Rothman et al, 1996; Dreyer et al, 1999) analysed mortality in a cohort of 285 561 * users of mobile phones from two carriers in the USA. Information on duration of use of phones was obtained from the billing records of the carrier. Mortality of the cohort was ascertained from the US National Death Index, but only for one year of follow-up. No relation was found between all-cancer, brain cancer or leukaemia risk and the use of handheld versus non-handheld phones (ie ones without an antenna in the handset), or minutes per day of use of handheld phones, or years of use of handheld phones. There were, however, small numbers of brain cancers (6) and leukaemias (15) in the analyses and the maximal categories of handheld use were 2 or more minutes per day (median 5) and 3 or more years of use (median 3.8).

Danish cohort

34 The second cohort study was from Denmark (Johansen et al, 2002a) and followed retrospectively 420 095 mobile phone users. Initially the investigators identified all the subscribers from 1982, when the service started in Denmark, to 1995 from the two Danish operators – 723 421 subscribers in all. Corporate customers were eliminated from the list, and then the investigators linked as far as possible the remaining subscribers to the Central Population Register for Denmark, with elimination of those who could not be unambiguously linked, duplicates, subscriptions after the study period, persons living in Greenland and the Faroe Islands, and those aged under 18 years at first subscription, as well as 53 individuals who asked to be excluded from the study. The eventual cohort consisted of 80.3% of the residential subscribers obtained from the phone company listings; 8% had begun subscriptions in 1990 or earlier, and 31% in 1993 or earlier. Information on cancer incidence in the cohort was ascertained by linkage to the Danish Cancer Registry, from which follow-up for death and emigration was also obtained to the end of 1996. The average follow-up for analogue subscribers was 3.5 years and for digital was 1.9 years. Standardised incidence ratios (SIRs) were calculated to compare cancer incidence rates in the phone users with Danish national rates allowing for sex, age and calendar period.

35 Risk of cancer incidence overall was significantly reduced in the cohort (SIR 0.89; 95% CI 0.86–0.92). The deficit was mainly due to a decrease in lung cancers and other smoking-related cancers, which the authors considered reflected the high socioeconomic

* 255 868 mobile phone users in the paper by Rothman et al; 285 561 analogue phone users in the paper by Dreyer et al.

status and hence presumed low smoking of the phone users. There were no cancer sites for which a significantly raised risk was found in the cohort, and in particular there were no excesses for cancers of the brain and nervous system (0.95; 95% CI 0.81–1.21), eye (0.59; 95% CI 0.25–1.17 (Johansen et al, 2002b) and salivary gland (0.72; 95% CI 0.29–1.49), or for leukaemia (0.97; 95% CI 0.78–1.21). Risks of brain and nervous system cancers and leukaemia did not vary by duration of digital phone use (similar analyses could not be conducted for analogue use), time since first subscription, age at first subscription, or use of analogue vs digital phones. There were no significant relations of risk to anatomical location or histology of brain tumours.

Discussion

36 Aside from the usual strengths and weaknesses of case–control and cohort designs (Rothman and Greenland, 1998), certain specific points should be noted about these methods when used for examination of risks related to the use of mobile phones.

Case–control studies

37 The case–control studies had no measurements of exposure, or even, except for that by Auvinen et al (2002), recorded billing information. Patterns of use of mobile phones are complex and difficult to recall with accuracy, and there is therefore great scope for misclassification of exposure in such reports. In particular, there is scope for bias, because of the publicity that there has been in recent years about the possibility that mobile phones might cause brain tumours; this might bias odds ratios for brain tumours after phone use upwards. The potential for misclassification is increased, unusually, because the tumour itself, as a consequence of its position in the brain, may affect the ability to remember or to think about past exposures*, and also because the tumour may affect phone use, by its effects on cognition and personality or because illness may lead to absence from work. Low grade tumours may be present for a considerable period before diagnosis, and hence recent phone exposure patterns could in part be a consequence of the tumour rather than the cause of it.

38 The use of hospital controls in the American case–control studies (Muscat et al, 2000, 2002; Inskip et al, 2001; Warren et al, 2003) and that by Stang et al (2001) gave potential for bias because the illnesses of the controls might themselves be associated (positively or negatively) with phone use. There is also a possibility of bias from different catchment populations for cases and controls, although in the Inskip et al study matching on proximity of residence to the hospital should have reduced this.

39 There is also a more minor difficulty in interpretation of the American brain tumour studies in that the interviews were conducted with the subjects themselves in some instances and with proxies in others, and there was potential for bias (although its direction is not predictable) because proxies were used more often for cases than controls. Similarly in the large Swedish study (Hardell et al, 2002a) 'help' from relatives in completing the questionnaire was given far more often for cases than for controls. The telephoning of selected postal respondents by Hardell et al (2002a) because their questionnaires were 'unclear' or of insufficient 'quality' leaves potential for bias, with respect both to the choice of those failing to meet these standards and in the telephone

* Particularly if it is a glioma, but uncommonly if it is a meningioma or acoustic neuroma.

questioning then undertaken. Very limited information in the paper does not suggest an appreciable bias for ever/never use, however.

Cohort studies

40 The cohort studies have avoided potential recall bias and interviewer bias by using billing information about phone use recorded before cancer diagnosis. These cohort studies also have the strength, compared with the case–control studies, that all tumours were included irrespective of their aggressiveness and hence whether interviews could be conducted, and that cancer outcomes (in the cohort defined for follow-up) were included without selection by whether the individuals concerned wished to participate. Studies based on billing records, however, have had the disadvantage that the recorded bill-payer may not be the sole user of the phone. [Among respondents to an American survey of phone users in about 1995 (71% response rate), the subscriber was the main user in 69% of subscriptions, and the sole user in 48% (Funch et al, 1996).] Furthermore, the cohort studies have not been able to conduct analyses of risk by side of phone use, they have included hands-free use without discrimination, and depending on the billing system they may not have included both outgoing and incoming calls. They have also lacked data on potential confounders. There is no obvious reason, however, from what is known of brain tumour and leukaemia causation, why such confounding, if there is any, should lead the cohort studies to fail to find a substantial association with phone use, if one exists.

41 The omission of corporate users from the cohort studies may have selected toward low exposure users, in the early years at least, for financial reasons. The Danish study (Johansen et al, 2002a) also has the bias that the study cohort constituted 15% of the reference group (the entire Danish population). This will tend to have biased toward the null the results for the study group compared with the reference group (Godward et al, 2001), although it will not have biased analyses conducted internal to the study group. In comparisons with the reference group, the tendency to obscure a raised risk, if there is truly one, may have been accentuated by the inclusion in the reference group but not in the study group of corporate users, who might on average have been the heaviest early users.

Conclusions

42 In reaching an overall conclusion from the published investigations, account must be taken of the size and quality of each study, and of the likelihood of bias, confounding or misclassification of exposures. In this respect among the cohort studies the Danish study stands out as being large, with up to 15 years of follow-up since first subscription, and with good quality cancer registration data that are probably virtually complete, whereas the American study was smaller, had extremely short follow-up and small numbers of relevant events, and considered mortality rather than cancer incidence (a less desirable outcome when trying to assess aetiology). Neither of the cohort studies gave any suggestion that mobile phone use causes raised risk of malignancy.

43 Among the case–control studies of brain tumours, that by Inskip et al (2001) is large, had high response rates, and appears well conducted. Like the other American study, by Muscat et al (2000), it has the disadvantage of hospital-based cases and controls* and

* Although this may well have been the best design available in the practical circumstances.

the possibility of selection bias in the types of individuals attending the particular hospitals. The studies from Sweden (Hardell et al, 1999a, 2002a) have at first sight the strength of population-based cases and controls, and the second of these studies was large (Hardell et al, 2002a). The apparently low response rate revealed by Ahlbom and Feychting (1999) for the first of these studies (Hardell et al, 1999a), however, leaves considerable uncertainty about the degree of selection that may have occurred in the cases included in the investigation (and possibly the controls too, if reporting of these in the paper was similarly unsatisfactory), and also about the dependability of the reporting of the study. Similar comments apply to the second Swedish study (Hardell et al, 2002a). The case–control study by Auvinen et al (2002) was based on billing records that avoid recall bias, and selection of cases and controls was from national records that render selection bias unlikely. There is potential, however, for misclassification of exposure in billing records (which would be likely to obscure risks, if they exist), as described above in relation to the cohort studies*. Also, the study had no information on the frequency or duration of calls.

44 The significant findings in subsets of data in the case–control studies by Hardell et al (1999a, 2002a) and Auvinen et al (2002) were not confirmed in the other studies, as follows.

45 The raised risk found in the first study by Hardell et al (1999a) for occipital plus temporal plus temporoparietal tumours ipsilateral to phone use might be a consequence of data-driven aggregation of anatomical sites, and reporting bias, as discussed earlier. The combination of sites has not been analysed by other authors, not even, tellingly, by Hardell et al in their next study (2002a). The raised risk of glioma for users of analogue phones found by Auvinen et al (2002), which appeared unlikely to be due to bias, was not indicated in the other studies: the largest American case–control study, mainly of analogue exposure, found a relative risk of 1.0 (95% CI 0.7–1.4) for glioma in relation to ever use of mobile phones (Inskip et al, 2001); the largest Swedish case–control study (Hardell et al, 2002a) found a relative risk of 1.1 (95% CI 0.8–1.6) for malignant brain tumours in relation to analogue phone use; and the largest cohort study found a relative risk of 0.9 (95% CI 0.7–1.2) for glioma in phone users (Johansen et al, 2002a).

46 The finding by Hardell et al (2002a) of a significant relation of brain tumour risk to analogue phone use was essentially a consequence of a raised risk for acoustic neuroma. In other case–control studies, however, relative risks of acoustic neuroma in phone users were 0.9 (CI not stated) (Muscat et al, 2002), 1.0 (95% CI 0.4–2.2) (Warren et al, 2003) and 0.8 (95% CI 0.5–1.4) (Inskip et al, 2001), and in the Danish cohort the standardised incidence ratio for cranial nerve sheath tumours, including acoustic neuroma, was 0.6 (95% CI 0.3–1.3). In the earlier study by Hardell et al (1999a) the relative risk for acoustic neuroma was 0.8 (95% CI 0.1–4.2). It is possible, given the size and long induction periods within the Hardell et al (2002a) study, that it found a real effect not detected in the other studies. Given the lack of raised risk of acoustic neuroma in the other studies, the methodological and reporting concerns about the Hardell et al study, the lack of evidence of dose–response, and the potential for

* The more so in Finland because of the high prevalence of corporate subscriptions, which were not included in the analysis.

reporting bias in acoustic neuroma patients*, however, there does not appear to be strong or convincing evidence for an association. The position is likely to be much clearer after publication of the case–control study coordinated by the International Agency for Research on Cancer (see Chapter 9, paragraph 12), which is expected to include 1000 cases of acoustic neuroma plus 1000 controls.

47 On the basis of exposure differentials, analyses of laterality of brain tumour in relation to laterality of phone use ought to be particularly informative in deciding about aetiology, but results on this have not been consistent, and there is potential for reporting bias on laterality of use. Interpretation is also complicated because the presence of a pre-diagnostic tumour may affect the laterality of use of the phone – for instance, hearing loss due to an acoustic neuroma may cause the subject to hold the phone to the opposite side.

48 The case–control study by Stang et al (2001) found a significantly, four-fold, raised risk of uveal melanoma in relation to mobile phone use, but the small size of this study, the unsatisfactory nature of the assessment of mobile phone use, and the use of two different designs within the study, with the positive result arising from the less satisfactory design, do not give confidence in the results. Furthermore, there was no raised risk of uveal melanoma in the Danish cohort data (Johansen et al, 2002b)†. In addition, if there were truly a raised risk of this magnitude, a marked effect on ocular melanoma trends would be expected in countries where mobile phones have been used for several years by a substantial proportion of the population: Danish data showed no such increase (Johansen et al, 2002b).

49 Overall, the epidemiological studies to date give no convincing evidence of a raised risk of brain tumour, leukaemia or other cancers in relation to mobile phone use. These studies are sufficient in aggregate to conclude that it is unlikely that there are large, short induction period carcinogenic effects of mobile phone exposure. The studies have had little power, however, to examine risks in relation to prolonged use, long induction periods since use, and high levels of daily or cumulative use, or to examine risks of rare types of tumour or effects on tissue very close to the handset, especially for small increases in risk. Furthermore, the current literature relates largely, although not entirely, to analogue rather than digital phone use. The comments above about lack of statistical power to examine risks in relation to long durations of use and long induction periods, apply even more strongly to digital than analogue phone exposure. If a hypothesised risk from phones relates to power absorption, then analogue phones would provide a more potent test of association than digital because the average power output tends to be considerably greater for the former (which do not have adaptive power control) than the latter. If, however, the risk was hypothesised to relate to certain other aspects of the exposure, then the more recent the technology, the shorter the induction period that can be examined in current analyses.

* As well as knowing that the location of their tumour is close to the phone, acoustic neuroma patients might also believe that there is an association because their tumour is connected with hearing, as (in a different way) is the use of the phone.

† An apparent relation of uveal melanoma to reported radar and microwave (but not specifically mobile phone) radiation was also seen in a case–control study by Holly et al (1996). No deaths from uveal melanoma were found, however, in over 40 years follow-up of 20 000 US Navy personnel with potential for high exposure to radar (Groves et al, 2002).

50 None of the studies to date has examined brain tumour risk in relation to the distance of the tumour origin from the phone antenna, other than in the broad sense of analyses by lobe of the brain and laterality of the tumour and phone use. This is important because RF fields are attenuated rapidly with passage through tissue, so that even ipsilateral areas of the brain can receive relatively low doses if they are medial or are greatly anterior to the antenna. If there were a real risk proportional to SAR, therefore, the risks observed in published analyses would have been diluted by inclusion of tumours distant from the RF source. Similarly, the exposure measures used to date have been crude proxies for degree of RF exposure (see Chapter 2), which depends for instance on the model of phone, position of its antenna and distance from the base station. Again this would tend to have diluted in published analyses any real risk related to RF exposure.

RADIOFREQUENCY FIELD EXPOSURES THROUGH WORK AND HOBBIES

51 Risks of cancer in relation to occupational RF exposures have been investigated in studies published over a period of more than 20 years and relating to exposures as early as the 1950s.

52 The literature has been reviewed on several occasions (European Commission Expert Group, 1996; Elwood, 1999; Moulder et al, 1999; Royal Society of Canada, 1999; IEGMP, 2000), and publications before the IEGMP report are therefore not reviewed here in detail. In brief, a wide variety of groups with potential for exposure have been investigated, including radar technicians in the US Navy (Robinette et al, 1980), radio and telegraph operators (Milham, 1985; Tynes et al, 1996), amateur radio operators (Milham, 1988), workers in dielectric heat sealing (Lagorio et al, 1997) and pulse testers (Muhm, 1992). Most interest has centred on brain tumour and leukaemia risks; Tables 7.3 and 7.4 summarise the major studies of these malignancies. In addition, there have been isolated reports of raised risks of testicular cancer (Hayes et al, 1990), male breast cancer (Demers et al, 1991) and uveal melanoma (Holly et al, 1996; Stang et al, 2001) in relation to RF exposure.

53 In general, although significantly raised risks have been found in certain studies, there is no consistent evidence of raised risk for any cancer site. Furthermore the studies have had several methodological weaknesses, especially with regard to exposure assessment (Swerdlow, 1999). In particular, none of the studies included measurements of RF exposure for the individual subjects. A few had sample measurements for areas where the work was undertaken or for samples of workers in the job, but most had no measurements at all and often not even an unmeasured assessment of dose categories within the study group. Indeed at their weakest, several studies, especially those based on routine data sources, have simply assessed cancer incidence or mortality risks for an occupational group with a particular job title, without evidence on the extent to which people in that job have raised RF exposure, if at all. The type of exposure examined has also varied greatly between studies – for instance in frequency, intensity, and duration – such that results from different studies cannot easily be synthesised.

TABLE 7.3 *Epidemiological studies of lymphatic and haematopoietic cancer in people potentially exposed to RF fields through work or hobbies*

Type of study	Study population	Exposure condition	Disease outcome	Number of exposed cases	Estimated relative risk (with 95% CI) *	Reference
Cohort	Radar technicians in US Navy	Occupations with high potential exposure to radar	Death from leukaemia	69	1.14 (0.90–1.44)	(Robinette et al, 1980) § Groves et al, 2002
Cross-sectional analysis of proportional mortality	Men age 20 + years in Washington State, USA	Radio and telegraph operators Radio and television repairmen	Death from lymphatic or haematopoietic cancer	15 12	1.37 1.27	Milham, 1985 §
Cohort	Amateur radio operators in California and Washington State, USA	Amateur radio operators	Death from lymphatic or haematopoietic cancer	89	1.23 (0.99–1.52)	Milham, 1988 §
Cohort	White male enlisted men in US Navy	Radiomen Aviation electronics technicians	Non-Hodgkin's lymphoma	2 1	0.6 (0.1–2.0) 0.4 (0.0–2.2)	Garland et al, 1988 §
Case–control	Men aged 20 + years in New Zealand	Radio and television repairmen	Leukaemia	2	7.9 (2.2–28.0)	Pearce et al, 1989 §
Cohort	White male enlisted men in US Navy	Radiomen Electronics technicians	Leukaemia	4 5	1.1 (0.3–2.8) 1.1 (0.4–2.6)	Garland et al, 1990 §
Cohort	Norwegian electrical workers	Occupations with potential exposure to RF fields	Leukaemia	9	2.85 (1.30–5.41)	Tynes et al, 1992 §
Cohort	Male electromagnetic pulse (EMP) test workers	Work on EMP test programme	Death from leukaemia	UC † 1 MC † 2	UC † 4.4 (0.1–24.3) MC † 7.7 (0.9–28.0)	Muhm, 1992 §
Cohort	Norwegian female radio and telegraph operators	Radio and telegraph operators	Leukaemia Lymphoma	2 5	1.1 (0.1–4.1) 1.3 (0.4–2.9)	Tynes et al, 1996 §
Cohort	Polish military personnel aged 20–59 years †	Occupational exposure to RF fields	Lymphatic and haematopoietic cancer	Not given 36	6.31 (3.12–14.32) 5.3 ($p < 0.01$)	Szmigielski, 1996 § Szmigielski et al, 2001
Cohort	Female employees in an Italian plastics factory	Exposure to RF fields through work in a dielectric heat sealing department	Death from leukaemia	1	5.0	Lagorio et al, 1997 §
Cohort	Men and women employed in the design, manufacture and testing of wireless devices	Work in occupations with moderate or high peak exposures to RF fields	Death from lymphatic or haematopoetic cancer	20	0.54 (0.33–0.83)	Morgan et al, 2000 §

* Confidence intervals, where shown, are as calculated by the authors.
† 25–59 years in Szmigielski et al, 2001.
‡ UC = underlying cause of death; MC = mentioned cause of death.
§ Reviewed in IEGMP (2000) report.

All-cause mortality data were published for few of these studies. Relative risks, where available, were: US radar technicians 0.69 (0.67 – 0.71); US radio amateurs 0.71 (0.69–0.74); EMP test workers 0.56 (0.31–0.95); Italian plastics workers 1.4 (0.7–2.7).

TABLE 7.4 *Epidemiological studies of brain and other nervous system cancers in people potentially exposed to RF fields through work or hobbies*

Type of study	Study population	Exposure condition	Disease outcome	Number of exposed cases	Estimated relative risk (with 95% CI) *	Reference
Cross-sectional analysis of proportional mortality	Men aged 20+ years in Washington State, USA	Radio and telegraph operators Radio and television repairmen	Death from brain cancer	1 2	0.38 0.59	Milham, 1985 †
Case–control	White men aged 30+ years from three areas of USA	Ever worked in a job with likely exposure to RF fields	Death from brain cancer	69	1.6 (1.0–2.4)	Thomas et al, 1987 †
Cohort	Amateur radio operators in California and Washington State, USA	Amateur radio operators	Death from brain cancer	29	1.39 (0.93–2.00)	Milham, 1988 †
Cohort	Norwegian electrical workers	Occupations with potential exposure to RF fields	Brain tumours	3	0.61 (0.13–1.78)	Tynes et al, 1992 †
Cohort	Norwegian female radio and telegraph operators	Radio and telegraph operators	Brain tumours	5	1.0 (0.3–2.3)	Tynes et al, 1996 †
Cohort	Polish military personnel aged 20–59 years †	Occupational exposure to RF fields	Tumours of the nervous system and brain	Not given 7	1.91 (1.08–3.47) 2.70 ($p < 0.01$)	Szmigielski, 1996 † Szmigielski et al, 2001
Case–control	Male personnel in US Air Force	Potential exposure to RF fields	Brain tumours	94	1.39 (1.01–1.90)	Grayson, 1996 ‡
Cohort	Female employees in an Italian plastics factory	Exposure to RF fields through work in a dielectric heat sealing department	Death from brain cancer	1	10.0	Lagorio et al, 1997 †
Cohort	Men and women employed in the design, manufacture and testing of wireless devices	Work in occupations with moderate or high peak exposure to RF fields	Deaths from cancers of the nervous system and brain	7	0.53 (0.21-1.09)	Morgan et al, 2000 †
Cohort	Radar technicians in US Navy	Occupations with high potential exposure to radar	Deaths from brain cancer	37	0.71 (0.51–0.98)	Groves et al, 2002

* Confidence intervals, where shown, are as calculated by the authors.
† 25–59 years in Szmigielski et al (2001).
‡ Reviewed in IEGMP (2000) report.

54 Although duration of exposure was analysed in a few studies (Thomas et al, 1987; Tynes et al, 1996), it was not in most. The power of the studies was often very limited, especially for analyses of risks of brain tumours and leukaemia, which are not particularly common malignancies. This included an absence of data in most studies on occupational exposure to other frequencies of radiation, including ionising radiation. Several of the studies were of cancer mortality rather than incidence, and for lymphatic and haematopoietic malignancies the disease category analysed varied between studies. Other, perhaps more modest, problems are that assessment of exposure outside the study setting (eg at home, or in previous jobs) was limited, or more often absent, and information on potentially confounding variables was generally either slight or absent.

55 There were methodological deficiencies in several studies: for instance, in the Polish military study (Szmigielski, 1996), more sources of information about RF exposure were used for cases than controls, giving scope for bias, and reporting of the study omitted crucial information about the numbers of subjects.

56 Taking into account the inconsistency of the findings and methodological shortcomings, IEGMP (2000) concluded that 'the overall balance of evidence from epidemiological occupational studies does not indicate that RF radiation affects the risk of cancer in people', but that the studies also gave no strong reassurance of the absence of a hazard.

57 Since publication of the IEGMP report, a few further studies have been published, as follows.

58 Stang et al (2001), in a small case–control study described above (see paragraph 28), examined risk of uveal melanoma in relation to occupational exposure to various sources of electromagnetic radiation. A significantly raised risk was found in relation to exposure to radio transmitting sets, including walkie-talkies, for at least several hours per day for at least six months (OR 3.3; 95% CI 1.2–9.2). There were risks of similar magnitude to this for exposures starting five or more years before diagnosis and exposures occurring over three or more years, and similar risks in the population-based and hospital-based data sets in the study. There was no raised risk in relation to radar exposure (OR 0.4; 95% CI 0.0–2.6), which was experienced by almost as many controls as experienced radio transmitter exposure.

59 A case–control study on testicular cancer (Baumgart-Elms et al, 2002) and a small case–control study on acoustic neuroma and intratemporal facial nerve tumour (Warren et al, 2003) already described (paragraphs 29–31) found no significant risks for occupational exposures.

60 Groves et al (2002) published an update of the cohort study by Robinette et al (1980) of mortality in 40 581 male US Navy veterans of the Korean war who had graduated into the Navy in 1950–54 and had potential exposure to high intensity radar. The cohort was divided, using consensus decisions based on measurement programmes, into men in job categories with 'low' RF exposure, usually well below 10 W m^{-2}, and those men (20 021 in number) in categories with 'high' exposure, who had potential for exposures exceeding 1 kW m^{-2}, although their usual exposures were below 10 W m^{-2}. Follow-up from graduation into the Navy up to the end of 1997 was obtained from beneficiary records of the Department of Veterans Affairs, which have been found elsewhere to contain about 95% of veterans' deaths, and also by matching

against the US Social Security Administration's Death Master File and against the US National Death Index for 1979–97.

61 The standardised mortality ratios (SMRs) for the overall cohort and for the high exposure cohort, compared with white males in the USA, were less than 1.00 for all causes, all cancers, and brain cancers. For leukaemia, the SMR for the overall cohort was below 1.00 and for the high exposure group was above 1.00 (Table 7.3), but not significantly so. There were no cancer sites for which significant excesses in the overall cohort or the high exposure group were reported. In analyses comparing the high exposure group with the low exposure group within the Navy cohort, there were significant excesses in the high exposure group for leukaemia overall (relative risk, RR, 1.48; 95% CI 1.01–2.17) and within this for non-lymphocytic leukaemia (RR 1.82; 95% CI 1.05–3.14), but this partly reflected the low standardised mortality ratios, compared with the general population, for the low exposure group.

62 The leukaemia excesses applied especially to aviation electronics technicians. There were not comparable increases in other high exposure occupations, however, and another study of US Navy aviation electronics technicians (Garland et al, 1990) found a diminished standardised incidence ratio for leukaemia of 0.3 (95% CI 0.0–1.9).

63 The study had the strengths of a large cohort with long duration of follow-up, relatively sophisticated attempts to estimate exposure (although not measures for the individuals in the cohort), and apparently reasonable quality follow-up (although the authors drew attention to some imperfections). The study only collected data on mortality rather than incidence of cancer, however, had no data on confounders, and had no data on exposures outwith the navy.

64 The absence of a substantially raised risk of cancer in this cohort after 40 years of follow-up argues against a major carcinogenic effect of exposure to RF fields in the radar frequencies.

65 Szmigielski et al (2001) published an update of their study of Polish military personnel (Szmigielski, 1996), extending the period covered from 1971–85 to 1971–90 and altering the age group covered from 20–59 to 25–59 years. The study is of an unconventional and not entirely clear design, aiming to compare cancer incidence in RF exposed and unexposed personnel. The paper states that the study population comprised all military career personnel in Poland during the study period. It is not stated whether women were included; there is no indication that the results were adjusted for sex. The study population was divided into RF exposed and non-exposed individuals in each year. The sources of exposure information for 1971–85 were military safety, service personnel and health department records for each subject plus hospital and central medical board data for those personnel who developed cancer. From 1985 unspecified measurements were made to assess maximum RF exposure levels in each type of military occupation, plus a questionnaire was given to personnel with newly diagnosed malignancy asking about their RF (and other) exposures. There were therefore more sources of exposure information for cancer cases than for non-cancer subjects, and scope for the 'exposed' group to have individuals added to it because they had had cancer and hence had been given an exposure questionnaire and had extra records examined (ie there was scope for an apparently raised risk of cancer to be found in the RF exposed group because of bias).

66 Cancer incidence in the personnel was ascertained from records of military hospitals and the central military medical board. It is unclear what diagnostic certainty or tests were required for inclusion of neoplasms, and whether the study included cancers diagnosed after leaving military service, in particular after leaving because of illness that later proved to be cancer. It is stated that cancers occurring from 1985 onwards were ascertained prospectively; by implication those occurring before then had been ascertained retrospectively.

67 Annual cancer incidence rates were calculated in subjects in RF unexposed occupations (average 120 600 personnel) and exposed occupations (average 3900 personnel) in the military by dividing the number of cancers occurring in these groups by the populations of the groups in that year. An (unweighted) average was then calculated of the rates for each year of the study period, and this average was taken to represent the study period overall. The ratio of this rate in exposed compared with unexposed personnel was taken as the relative risk. The all-age rates, and the relative risks, appear to have had no adjustment for potential age differences between the exposed and unexposed groups. Statistical methods for analysis are unclear; it is simply stated that 'A battery of statistical tests were used for analysis and correlation of results'.

68 In the analyses (Szmigielski et al, 2001), 2355 cancers in unexposed personnel and 138 in exposed personnel were included, with an overall relative risk of cancer in exposed personnel of 1.83 ($p < 0.01$). Significantly raised rates of cancer incidence in exposed personnel were recorded for cancers of the oesophagus plus stomach, colon plus rectum, skin including melanoma, and nervous system, and for haematological plus lymphatic malignancies. Rates of cancers overall and of haematopoietic plus lymphatic neoplasms were greater for exposed than unexposed personnel in each of four age subdivisions of the data, and were highly significantly ($p < 0.01$) and at least three-fold raised in exposed personnel for each of Hodgkin's disease, non-Hodgkin's lymphoma, acute myeloid leukaemia, chronic myeloid leukaemia, acute lymphoblastic leukaemia, and chronic lymphocytic leukaemia. All-cancer rates showed some evidence, but not consistently, of greater rates in more highly exposed military occupations.

69 The unsatisfactory design of this study, the likely biases, and the improbable results, both in the light of the existing literature on RF effects and in the light of the general epidemiology of cancer, make the results ones to which little weight can be given.

Conclusions

70 It remains the case, as concluded by IEGMP (2000), that the literature overall does not indicate that occupational exposures to RF fields affect the risk of cancer, but also it does not give strong evidence that no risk exists.

RESIDENCE NEAR RADIO OR TV TRANSMITTERS

71 IEGMP (2000) summarised studies published until 2000 on cancer risks in people living near radio or TV transmitters. Such studies had been published from the USA, Britain and Australia, and had mainly analysed risks of childhood leukaemia, lymphoma and brain cancer, although a UK study addressed a wider range of tumours and ages (Dolk et al, 1997). In addition to these studies, IEGMP noted two others that have not been published in the peer-reviewed scientific literature – of people living

near a military microwave generator–detector system in Latvia, and of staff and their dependants in American embassies in Eastern Europe. These studies could not be evaluated by IEGMP because they had not been published in detail regarding their methods and results.

72 IEGMP noted great limitations of the studies to date, and indeed of studies of their general design, as follows.

73 The studies have not used measurements of radiation levels to assess exposure, but instead have taken distance from the broadcasting mast as a proxy for exposure level. For the reasons discussed in Chapter 2, however, this assumption is far from correct. For instance, because the broadcast beam is aimed distantly, the areas closest to the mast, rather than having the greatest exposure levels, instead have relatively low levels. Lack of a direct relation of dose to distance is also brought about by perturbations of RF levels by ground reflections and signal reductions by buildings, vegetation and undulations.

74 The studies have been of an 'ecological' design, ie they have assessed cancer risks in populations in relation to the residential locations of these populations, rather than risks in individuals in relation to their personal locations or exposures. Such studies are methodologically weaker than individual-based studies, because even if populations with greater exposure have in aggregate greater risks, it does not follow that the individuals with disease within these populations were individuals with high exposure. Confounding variables might explain high risks, and the ecological studies could not adjust closely for potentially confounding factors, which to the limited extent they were available were necessarily analysed only at a population level.

75 Furthermore, the exposure variable analysed in the residential studies took no account of the proportion of time spent by the populations in places other than their homes, or of behaviours affecting exposure when at home (eg time spent indoors vs outdoors), or of exposures from sources other than masts (eg from other RF sources near or in the homes, and from phones and occupational exposures). It is a weakness of the ecological design that it would be difficult or impossible to gain satisfactory data on these variables for entire populations.

76 The studies have analysed risks in relation to place of residence at the time of the study outcome, ie cancer incidence or death, rather than at the time relevant to causation, which is unknown but at the least must be earlier than the recorded 'incidence' date, probably by several years.

77 For childhood cancers, the studies have often had low power, because of small numbers of cases.

78 Finally, several of the analyses were essentially 'cluster' analyses (Rothman, 1990), that had been undertaken *because* of the observation of an apparent excess of cases of a particular malignancy over a particular time period in a particular location and age group. As the diagnostic, time, location and age categories chosen for analysis were driven by the observed cases, such clusters, even if nominally statistically significant, cannot be distinguished from chance clusterings. Hence at best they contribute no more than a hypothesis for testing in an independent data set.

79 Since the publication of the IEGMP report, one further residential study has been published, from Italy. This reported on leukaemia mortality in adults, 1987–98, and leukaemia incidence in children, 1987–99, among 50 000 people living within 10 km of

the Vatican radio transmitters (Michelozzi et al, 2002). The radio station was installed in 1957 and had numerous powerful transmitters with frequencies from 527 to 21 850 kHz. Eight cases of childhood leukaemia occurred in the study area. There was a significant trend of decline in risk of childhood leukaemia with distance from the radio station ($p = 0.04$). All but two of the cases had lived in the same dwelling since birth, and exclusion of these two cases left a near-significant trend ($p = 0.06$). The risk of childhood leukaemia in the circular area up to 6 km from the station was borderline significantly above that expected from general population rates for Rome (SIR 2.2; 95% CI 1.0–4.1). Risks in 2 and 4 km circles were greater, but based on smaller numbers they were less close to statistical significance.

80 For adults overall there was no significant risk within any particular circle of distance from the transmitting station nor a trend in risk with proximity. There was a significant decline in risk with distance for males but not females, but there is no obvious *a priori* reason why a sex difference of this type should occur. No data were available to determine exposure levels by distance from the station, although certain measures for short time periods at some locations were available, with electric field strength values up to 95 $V\,m^{-1}$. Adjustment for socioeconomic status did not alter the results. The cautions noted above about interpretation of ecological studies of risks in relation to proximity to masts apply to this Italian study also. For these reasons the Italian study does not provide substantial evidence for RF aetiology of leukaemia.

Conclusions

81 IEGMP concluded, and this conclusion remains valid, that the balance of evidence from the residential studies did not indicate a hazard, but equally that it did not provide strong evidence against one.

SUMMARY

82 The potential relation of RF field exposure to risk of cancer has been investigated in studies of users of mobile phones, people with occupational or hobby RF exposures, and populations living near TV and radio transmitter masts.

83 Risks of cancer in relation to mobile phone use have been investigated in five case–control studies of brain tumours and three other case–control studies, as well as in two cohort studies. In seven of the case–control studies, exposure was assessed by interview of the study subjects and in one it was ascertained from phone subscription records. Both of the cohort studies used subscription records and one, in Denmark, was very large (over 400 000 users), with up to 15 years of follow-up since first subscription and with cancer registration data that were virtually complete. The cohort data gave no indication of raised risk of nervous system tumours, leukaemia or any other malignancy in relation to phone use. Although there were some significantly raised risks of brain tumour within certain of the case–control studies, these did not receive support from the other studies, nor were there dose–response effects or other features that might indicate likely aetiology. One case–control study found a large raised risk of uveal melanoma in relation to occupational mobile phone use, but the study was small and had several methodological deficiencies as well as lack of consistent support from other epidemiological evidence.

84 Risks of cancer incidence or mortality have been ascertained in cohort studies of a range of potentially RF-exposed occupational groups as well as amateur radio operators, and certain case–control studies of brain tumour and leukaemia have also investigated RF field exposure as a potential aetiological factor. The studies have generally had poor or non-existent exposure measurement, poor or no information on potentially confounding variables, and often low power. In aggregate, they give no indication that RF field exposure in occupational circumstances affects the risk of cancer in man. Where significantly raised risks have been found, these have not been supported by the remainder of the literature. Reports of raised risk of testicular cancer, male breast cancer and uveal melanoma in relation to RF exposure have been published, but again without support from the literature overall or indications within the studies that a causal relation was the likely explanation.

85 Studies of cancer risks in people living in the vicinity of radio or TV transmitters have been conducted in the UK, USA, Australia and Italy. They have had the weaknesses of an ecological design, lack of data on RF exposures from sources other than these transmitters, lack of data on confounders, and often the weakness that the investigation was undertaken because a cluster of cases had already been observed. Furthermore, the studies have taken distance from the broadcasting masts as a proxy for exposure level without data to indicate that this was a valid proxy. They have given a very weak test of the possibility that residential exposure to RF transmission might affect cancer risk and do not provide any substantial evidence of such an association.

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8 Conclusions

1 The present report by the Advisory Group on Non-ionising Radiation considers scientific research related to the possible consequences for health of exposure to radiofrequency (RF) fields. It is principally concerned with studies published since the report by the Independent Expert Group on Mobile Phones (IEGMP), which was issued in May 2000. The present report covers cellular and animal studies as well as epidemiological investigations. It also examines sources of RF fields. It does not specifically consider TETRA signals, the subject of an Advisory Group report in 2001, but no information has been identified that alters the conclusion about these signals in the 2001 report.

ELECTROMAGNETIC FIELDS, SOURCES AND EXPOSURE

2 The RF fields to which people are exposed cover a wide frequency range with very variable signal characteristics and come from a wide range of devices. Considerable advances have been made in exposure characterisation and dose assessment for the RF fields to which people may be exposed. Published information tends to give exposure maxima rather than time-integrated exposures, which are generally lower and are more appropriate for comparison with guidelines. Instruments incorporating electric and magnetic field sensors that are worn on the body are not sufficient on their own for ensuring compliance with exposure guidelines but can be used for obtaining broad estimates of exposure for epidemiological studies. There are few situations where the general public is likely to be exposed to fields that exceed the reference levels contained in current exposure guidelines. Where such cases do arise, and for some occupational exposures where there is a greater likelihood of exceeding reference levels, dosimetric approaches using physical and numerical modelling are required to establish whether or not the basic restrictions on exposure are met.

3 Measurements made by the Radiocommunications Agency and NRPB of exposures to RF fields of members of the public near to mobile phone base stations have continued to demonstrate that exposures are generally extremely small fractions of guideline levels.

CELLULAR STUDIES

4 Studies on cells in culture allow possible mechanisms of interaction of RF fields with organs and tissues to be examined in a controlled environment. Most of the studies into the role of RF fields as a potential carcinogen do not show a genotoxic effect at non-thermal levels. The results from micronucleus assays, which are a measure of damage to chromosomes, are contradictory.

5 Studies into heat shock protein expression, as an indicator of stress, are intriguing in that the experiments appear to show positive effects, even at low values of specific

absorption rate (SAR). There is, however, no consistent pattern between studies as to which heat shock protein is stimulated. Other biological changes in cells due to RF exposure, when found, are small, tending to be only just larger than the uncertainty in the precision of the measurement technique used. The implications for human health of any such biological changes can only be conjectured.

6 IEGMP examined studies on the movement of calcium ions in cells, as a measure of cell function, and concluded that the evidence that low level amplitude modulated RF can cause release of calcium from tissues was contradictory. This issue was subsequently examined in greater depth by the Advisory Group with regard to the use of TETRA communications. It was concluded that, although generally better-designed studies have not detected an increase of calcium movement in tissues as a result of exposure to a variety of conditions and modulation of RF fields, further research should be undertaken. At present, there are too few investigations of calcium flux in cells using modern techniques to draw firm conclusions. However, two recent well-designed studies have been reviewed and both show no change in the cellular concentration of calcium ions – a sensitive indicator of cell pathology – in response to RF exposure, even when using pulse modulation, thus adding further doubt about the existence of a specific pulse modulation effect on calcium flux.

ANIMAL STUDIES

7 Recent animal studies on effects of RF exposure have mainly used fields characteristic of mobile phone communication systems. With regard to possible carcinogenicity, several studies using established animal models have found no evidence of a genotoxic, mutagenic or carcinogenic effect. In particular, the findings of an extensive, better-conducted study do not corroborate an earlier report that RF exposure causes an increase in lymphoma incidence in a transgenic mouse strain predisposed to lymphoma induction. In addition, RF exposure did not affect survival and spontaneous tumour incidence, the incidence of x-ray induced lymphomas, spontaneous and chemically induced brain tumours, or chemically induced mammary or skin tumours in a number of long- and medium-term rodent assays.

8 Male fertility has long been recognised as susceptible to heat, and animal studies have confirmed a similar susceptibility to RF exposure at thermally significant levels; recent studies support the view that such effects do not occur at lower levels of exposure. The developing central nervous system in the embryo and fetus seems to be the system most susceptible to maternal hyperthermia. This is because of the limited number and restricted physical location of the cohorts of proliferating cells from which the brain arises and the precision required for the complex neuronal architecture essential to proper brain function. Subtle postnatal behavioural changes have been observed in the offspring of rats exposed to RF fields at levels usually associated with an increase in maternal body temperature. However, behaviour was not significantly affected in offspring exposed to non-thermal levels of RF characteristic of GSM frequencies.

9 Most studies in animals have not reported any RF-field-dependent responses on the brain and nervous system, particularly with regard to changes in gene expression

and the permeability of the blood–brain barrier: the results of a recent high profile, but methodologically limited, study from Sweden fail to provide any convincing evidence of a field-dependent effect on the blood–brain barrier. It is possible that changes in cholinergic activity in the brain may be induced by RF exposures, but these may reflect thermoregulatory responses. Such changes in neurotransmitter function might predict effects on spatial learning and memory, but the evidence for this is equivocal: two studies from one laboratory reported field-dependent deficits in behaviour using pulsed microwaves, but these effects were not confirmed in two independent studies using GSM signals. In addition, significant effects on the performance of a related task were seen only when exposure resulted in marked elevations of body temperature.

BRAIN ACTIVITY AND COGNITIVE FUNCTION STUDIES

10 Scientific evidence regarding effects of RF field exposure from mobile phones on human brain activity and cognitive function published since the IEGMP report has included results both supporting and against the hypothesis of an effect. Although some recent studies of human brain activity have reported further positive effects of mobile-phone-like signals, the pattern of effects varies considerably between studies, none appears to have been independently replicated, and any implications for health are unclear. A number of studies have reported improved cognitive performance (faster reaction times and fewer errors) in the presence of mobile-phone-like signals, but some of these have methodological problems and cannot exclude other possible explanations. In addition, a better-conducted study has not corroborated the previous findings of faster reaction times in the presence of mobile phone signals described in the IEGMP report. A recent study has suggested some effects of UMTS signals on both subjective well-being and cognitive function, but the investigation needs replicating before a firm conclusion can be drawn. Overall, the evidence for a direct effect of mobile phone fields on cognitive performance is inconsistent and remains inconclusive.

CLINICAL STUDIES AND NON-CANCER EPIDEMIOLOGY

11 Acute exposure to high intensities of RF fields can cause thermal injury to tissues. However, the exposures that have led to these injuries have been well above the guideline levels currently recommended in the UK.

12 There is convincing evidence that pulse modulated RF fields with frequencies between 200 MHz and 6.5 GHz can cause auditory stimulation at exposure levels as low as 400 $\mu W\ cm^{-2}$. This appears to result from thermoelastic expansion of tissues in the head as a consequence of minute fluctuations in temperature. Although the resultant perception of sound might be considered a nuisance, there is no reason to suspect that it has any long-term adverse impact on health.

13 Epidemiological evidence on the induction of cataracts by microwave radiation is of variable quality. Many of the published reports do not provide quantitative data on exposures, or on the reliability of the methods by which pathology in the lens was

assessed. There is no indication that clinically important cataracts occur with increased frequency in microwave workers.

14 Some individuals report symptoms (most commonly of hotness or altered sensation over the ear and adjacent parts of the scalp) when they use mobile phones. It is possible that localised heating occurs as a consequence of radiation from the phone's antenna or through conduction from the handset. The mechanism underlying other symptoms and associated clinical abnormalities is uncertain, but in some cases, at least, could be psychological.

15 A number of studies have examined other possible health effects of exposure to RF fields in people who are occupationally exposed. These include: effects on sperm production in military personnel and other RF-exposed workers; 'neurasthenic' symptoms in people exposed to RF fields through work or the use of mobile phones; spontaneous abortion among physiotherapists who used microwave diathermy around the time of conception; and congenital malformations following maternal occupational exposure to RF fields during pregnancy, principally in physiotherapy. For none of these effects was a clear effect demonstrated and many of the studies had methodological difficulties including the potential for recall bias and small numbers of cases. The studies were too limited to rule out the possibility of an effect.

16 There have been some reports of haematological abnormalities in workers exposed to RF fields. These have generally been minor, as well as being inconsistent between studies. The findings do not suggest a hazard.

17 Clinical and epidemiological data do not suggest an effect of RF fields on other non-cancer health outcomes.

CANCER EPIDEMIOLOGY

18 Several further epidemiological studies of cancer risk, especially in relation to mobile phone use, have been published since the IEGMP report. Although there have been positive findings in some studies for risks of specific cancers in relation to mobile phone use or to occupational or residential RF field exposure (or potential for exposure), no relation has been shown consistently. There has also not been a convincing demonstration of a dose– or duration–response relationship. Overall, none of the categories of epidemiological data gives persuasive evidence that RF field exposure causes cancer. It should be noted, however, that the exposures concerned have varied greatly in frequency, dose, anatomical location of exposure and time course of exposure, such that it is arguable to what extent the epidemiological literature on occupational, environmental and phone exposures can be regarded as an analysis of a single aetiological question.

19 The studies conducted to date have had indirect information on RF field exposure, which may have diluted real effects, if there are any. The design of the studies has often been deficient, and data on potential confounders have been few or absent. The power of many of the studies has been low. Hence, although the studies do not suggest a raised risk of cancer, they do not rule one out, especially in relation to large cumulative exposures to mobile phones and possible effects occurring many years after their use.

OVERALL SUMMARY AND CONCLUSIONS

20 This report examines possible health effects of exposure to radiofrequency (RF) fields, with an emphasis on studies conducted since the review by the Independent Expert Group on Mobile Phones (IEGMP) in 2000. There are many sources of RF fields – at work, at home, and in the environment – but recent emphasis in health-related studies has been on mobile phones and broadcasting masts. Studies reviewed by IEGMP suggested possible cognitive effects of exposure to RF fields from mobile phones, and possible effects of pulse modulated RF fields on calcium efflux from the nervous system. The overall evidence on cognitive effects remains inconclusive, while the suggestions of effects on calcium efflux have not been supported by more recent, better-conducted studies. The biological evidence suggests that RF fields do not cause mutation or initiate or promote tumour formation, and the epidemiological data overall do not suggest causal associations between exposures to RF fields, in particular from mobile phone use, and the risk of cancer. Exposure levels from living near to mobile phone base stations are extremely low, and the overall evidence indicates that they are unlikely to pose a risk to health. Little has been published specifically on childhood exposures to RF fields, and no new substantial studies on this have been published since the IEGMP report.

21 In aggregate the research published since the IEGMP report does not give cause for concern. The weight of evidence now available does not suggest that there are adverse health effects from exposures to RF fields below guideline levels, but the published research on RF exposures and health has limitations, and mobile phones have only been in widespread use for a relatively short time. The possibility therefore remains open that there could be health effects from exposure to RF fields below guideline levels; hence continued research is needed.

9 Research Recommendations

1 The following recommendations are made for further research into possible health effects from exposure to radiofrequency (RF) fields. These should be seen in the context of the substantial programme of ongoing RF health effects research in the UK funded by the Mobile Telecommunications and Health Research (MTHR) Programme and government departments (see Appendix C).

ELECTROMAGNETIC FIELDS, SOURCES AND EXPOSURE

2 Several recommendations can be made to improve the quality and interpretability of future health-related research. The dosimetry in many published studies is unclear, often because no dosimetry measurement was performed in the actual experimental setting. Future experimental research should control the parameters of the RF signal directly, rather than relying upon the normal operation of commercial mobile phone handsets, and should measure the SAR in the actual experimental setting and under the conditions of exposure. Dosimetry will need to be developed in conjunction with any epidemiological study for ensuring sound exposure assessments.

CELLULAR STUDIES

3 There is still a need for a cellular model that has a robust response to RF exposure and that can be transferred between independent laboratories. The Advisory Group is aware of further studies comparing the effects of pulsed with continuous wave signals on cellular calcium ion flux. Whether more studies are required will need to be reviewed in the light of these findings. Another potentially promising area for further research is the induction of heat shock proteins in cells by RF exposure. Most of the reported *in vitro* studies have shown positive effects, but this research area would benefit from their independent replication.

ANIMAL STUDIES

4 There is no direct experimental evidence to suggest that exposure to RF fields increases the risk of cancer. However, recently developed animal models with targeted gene mutations that predispose the animals to brain tumours – particularly glioblastoma, a leading cause of brain cancer in human beings – may prove useful in further animal studies.

5 The central nervous system seems to be particularly susceptible to heat. However, possible effects on the development of the cortex, known to be particularly susceptible to other harmful agents, and the behavioural consequences of these effects on the nervous system have not been fully explored. In addition, it is not clear to what extent the increased susceptibility of the embryo and fetal central nervous system to raised body temperature continues during subsequent postnatal development through to adolescence. Such uncertainties can only be addressed through further investigation.

6 The least questionable evidence for low level RF effects on neurobehavioural function relates to the changes in cholinergic and opioid activity observed in studies using whole-body SARs of about 1 W kg^{-1}. Field-induced changes in cholinergic function might predict effects on learning and memory but the evidence for such effects is unclear, too few tasks and exposure conditions have been examined. Further studies should be carried out of cholinergic and opioid activity in the brain and associated behavioural or cognitive responses in animals. In addition, reported changes in excitability of hippocampal slices *in vitro* following exposure to very weak RF fields require independent verification.

BRAIN ACTIVITY AND COGNITIVE FUNCTION STUDIES

7 More research is needed to investigate what impact, if any, neural activity changes after RF field exposure have on cognitive performance – for example, by measuring EEG patterns during specific cognitive tasks that have previously shown sensitivity to RF field exposure. Any possible health outcomes that may be associated with the altered EEG patterns caused by RF fields from mobile phones should also be identified. Finally, the biological mechanism whereby RF field exposure could alter EEG patterns remains unclear. Future cellular and animal studies may provide useful information about possible mechanisms underlying any EEG effects.

8 Possible effects of mobile phone signals on cognitive function could have important implications for health, and should be researched further. Future research should carefully control exposure levels, and should ensure that both participants and researchers are blind to exposure conditions. There has been little or no attempt to standardise cognitive tasks used across different experiments or different laboratories. Future research must be open to the possibility that performance on any cognitive task could potentially show RF field exposure effects. However, an overview of the balance of evidence across studies would be easier if the search for positive effects focused on a restricted number of standardised cognitive tests, with high face validity and proven sensitivity. Given the rapid pace of technological change in mobile telephony, standardisation of cognitive testing will be particularly important in assessing whether any new forms of RF signal do or do not affect cognitive function.

9 Previous research has often lacked statistical power, or proved difficult to replicate. Further research would therefore benefit from a multicentre approach, with identical experimental studies being carried out in parallel in two or more independent laboratories. International co-operation between research institutions should be encouraged as a means of achieving this.

CLINICAL STUDIES AND NON-CANCER EPIDEMIOLOGY

10 On the basis of the studies reviewed, no priorities for further epidemiological research on non-cancer outcomes have been identified. There are uncertainties, but nothing suggestive of an important health concern that is being missed. Any recommendations would therefore depend on suspicions from *in vitro* or *in vivo* laboratory studies.

11 It would be helpful to carry out further experimental trials on individuals who claim to be sensitive to RF fields and suffer acute symptoms from the use of mobile phones.

CANCER EPIDEMIOLOGY

Mobile phones

12 A large international case–control study is currently underway coordinated by the International Agency for Research on Cancer. It is expected to include 6500 cases of brain tumour from 13 countries, as well as 1000 cases of acoustic neuroma and 700 cases of salivary gland tumour, plus a similar number of controls, who are being interviewed using an extensive questionnaire about mobile phone use. The study also includes a methodological investigation about exposure assessment. There is not currently an international study of leukaemia risk in relation to mobile phone use, but there is such a study in the UK, which is expected to include about 900 cases and 900 controls. In view of the size and scope of these studies, the Advisory Group does not believe there is a case for inaugurating further general population case–control studies of cancer in relation to mobile phone use in the UK until the results of the studies now underway are known.

13 Future studies need to address the shortcomings of those published to date: ie to study longer periods of use, longer induction periods and greater cumulative exposures, to obtain more precise estimates of exposure (although with the difficulty that the appropriate metric is unknown), and to analyse risk according to the anatomical locations of the tumour and antenna. Examination of risks for longer induction periods is desirable, both intrinsically and also because it may avoid the bias in analyses of shorter periods that pre-diagnostic effects of the brain tumour might alter phone use, and hence distort any association.

14 Continuing follow-up and analyses of cohort studies already underway would be desirable, as would further cohort studies (or addition of mobile phone information to ongoing cohorts), if practical. Nested case–control studies may have the potential to address some of the deficiencies of cohort studies for exposure assessment (eg to gain data on whether the bill payer was the phone user). Specifically for TETRA phone systems, the Advisory Group noted in 2001 the need for the working practices and conditions of exposure of TETRA users to be characterised, and for records of use to be kept, in order that they would be available for potential future epidemiological studies.

15 Although routinely collected data on cancer incidence are a blunt instrument by which to try to ascertain whether or not aetiology occurs, they could nevertheless give useful information on whether there are likely to be major aetiological effects of mobile phone use on cancer risk over the induction periods through which a substantial proportion of the population has passed. Examination of such associations would be greatly improved if data were available on the age- and sex-specific prevalence of phone use over time within countries. Even without this, however, it might be expected that if there were major effects of phone use on incidence of particular cancer(s), then after a suitable induction period this ought to become apparent in countries such as Norway and Sweden, where prevalence of use rose earliest, and later should become apparent in countries such as Italy or France, where widespread take-up of mobile phones occurred later. There are, of course, many factors, mostly unknown, that may influence brain tumour trends, so that data from any one country would not in themselves be persuasive. International data on brain tumour incidence trends in the age groups most exposed, however, although they could not address subtle or long-duration effects, would at least address whether there are likely to be major short-induction period effects of mobile phone use on incidence of these tumours.

Occupational exposure

16 Again there is a need for better studies rather than simply for more. In particular, the studies need to be of occupational groups for whom measurements show that there is genuinely a substantially raised exposure to RF fields. If the studies are to be more informative than those so far, a key requirement will be for improved exposure measurement (or improved estimation of exposure) for individuals, or at least for occupational groups. It would be desirable, as far as practical, that the studies should measure the intensity and timing of RF field exposures, and also that they should include some assessment of major RF field exposures from sources other than the current occupation – ie domestically, from mobile phones, and from previous jobs. Ideally, exposure assessment needs to be anatomical site (organ)-specific, because some sources result in greatly differing doses to different parts of the body. It is a difficulty in these prescriptions, of course, that the appropriate exposure metric is unknown.

Exposures from broadcasting and mobile phone masts

17 The methodological barriers to conducting valid assessments of cancer risks in relation to these low level exposures are very great, as described in Chapter 7. In addition to the difficulties described there regarding radio and TV broadcasting masts, for analyses in relation to mobile phone masts there is the further difficulty that their locations have multiplied rapidly and continue to increase. This would make calculation of historical exposures harder.

18 If future studies are conducted, they need to be in locations where appreciable geographical variations in RF field exposure levels attributable to masts have been demonstrated and characterised by measurements in the study area. At present it seems likely that the most useful information on the possibility of a substantial carcinogenic effect of residential exposure to RF field from broadcasting/phone masts will come from extrapolation from results for other, more highly exposed groups – for instance, from studies of occupationally exposed populations.

Appendix A

INSTRUMENTATION

MEASUREMENT OF ELECTRIC AND MAGNETIC FIELDS

Electric field strength

Electric fields can be measured using suitable antennas such as small dipoles. If a single dipole is used, measurements are made in three orthogonal directions to obtain the components: E_x, E_y and E_z. The total field, E, is then given by

$$E = \sqrt{E_x^2 + E_y^2 + E_z^2}$$

Magnetic field strength

Magnetic fields are usually measured with small loop sensors – the current induced in the loop is proportional to the magnetic field strength passing through it. If a single loop is used, measurements are made with the loop axes in three orthogonal directions and the total field, H, is given by

$$H = \sqrt{H_x^2 + H_y^2 + H_z^2}$$

Power density

The power density, S, is usually determined from separate measurements of E and H. In the far-field region, S can readily be obtained from the expression $S = EH$. In the near-field, and where scattering, reflections or multiple sources are present, the field configurations, and hence the determination of S, can be extremely complex.

EQUIPMENT

For RF exposure assessment, field measurement equipment can be segregated into two types, broadband and narrowband. Broadband instrumentation usually does not contain frequency information and will indicate field strength independent of frequency. Narrowband instrumentation enables assessment of both frequency and field strength information over a selected frequency bandwidth. Spectrum analysers are often used for this purpose. Broadband instrumentation is the most widely used for RF hazard assessment due to its ease of use and portability. Narrowband instrumentation is used where frequency resolution and high sensitivity are required.

Narrowband equipment

Narrowband assessment is undertaken where measurements have to be taken on a large number of frequencies with different limits and relatively small signal strengths. Dipoles, loops and horns, which are commonly used for field measurements, are polarisation sensitive. To assess equivalent field strength the antenna used is rotated in three orthogonal directions or orientated for maximum signal strength. Antennas that are large compared to the wavelength are unsuitable for evaluating rapidly changing amplitudes over small regions of space.

FIGURE A1
Narrowband measurement equipment showing log-periodic antenna, spectrum analyser and computer control

Broadband measurement devices

Instruments covering a broad band of frequencies for field strength measurements consist of the field sensing probe and signal display instrument. Physically small dipoles are used in electric field probes and physically small loops in magnetic field probes. The detection of RF voltage usually takes place in the probe sensing element and the rectified voltage is processed and displayed by the instrument.

Usually probes are designed to either indicate one field component or the sum of all field components. Probes with a single sensor element respond only to one field component and require orientation to obtain the maximum value. Multiple sensor arrangements in suitable configurations can be used to sum the spatial field components and enable measurements independent of polarisation and direction of incidence.

FIGURE A2
Example of a broadband RF radiation measuring instrument

Body current instruments

The measurement of body currents induced by exposure to RF fields can be ascertained by evaluating current flowing to ground using either parallel-plate or current transformer approaches. Both techniques allow measurements up to approximately 100 MHz and in some cases personal current meters using transformers have been designed to extend beyond 200 MHz.

FIGURE A3 *Personal current meter being used to measure body currents when operating a PVC welding machine*

Personal RF dosemeters

A new generation of body-worn instruments has become available for continuously monitoring electric field strength (and in some cases also the magnetic field strength). These instruments can be programmed to sound an alarm and/or illuminate lights when the field strength exceeds a set threshold, eg 50% of the ICNIRP reference level. Some of the instruments also include a logging facility in order to sample and store the field strengths at regular intervals over a period of time.

FIGURE A4 *Typical personal RF dosemeter designed to be clipped to a wearer's body*

The field strength at the body surface is heavily perturbed and different to the field strength that would be found at the same location in the absence of the body. Care is therefore required in the interpretation of the readings from body-worn instruments and a rigorous calibration would have to take account of the field perturbation by the body.

The detectors in personal RF dosemeters produced to date are of a broadband type and so lack the sensitivity required for them to be used in studies of people exposed at environmental levels, eg when living near to radio transmitters. Detection thresholds on the most sensitive instruments are around 1% of the ICNIRP occupational reference level.

Appendix B

ICNIRP EXPOSURE GUIDELINES

In developing exposure guidelines, both the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 1998) and NRPB (1993) have reviewed studies of exposed human populations, biological studies and the dosimetry of electric and magnetic fields.

The approaches by ICNIRP and NRPB with regard to the evaluation and use of epidemiological data are entirely consistent and the broad base of biological data reviewed is similar.

The guidelines on restrictions on exposure to electromagnetic fields recommended by both ICNIRP and NRPB are based on biological data relating to thresholds for adverse *direct* and *indirect* effects of acute exposure. Direct effects are those resulting from the interactions of electromagnetic fields with the human body. For exposure to RF fields above about 10 MHz, which include microwaves, the restrictions are intended to prevent the adverse effects of whole- and partial-body heating. Indirect effects are those resulting from an interaction between electromagnetic fields, an external object such as a vehicle or other mechanical structure and the human body. For these effects restrictions on exposure to RF fields are intended to avoid burns.

Recommendations to prevent adverse direct effects are based on information on the interactions of RF fields with body tissues and are termed *basic restrictions*. Compliance with the basic restrictions cannot, however, be easily determined directly. *Investigation levels* (NRPB) or *reference levels* (ICNIRP) are therefore recommended as values of measurable field quantities for assessing whether compliance with the basic restrictions has been achieved.

The basic restrictions for occupational exposure in the ICNIRP guidelines do not differ in any significant way from those previously recommended by NRPB. For members of the public, however, ICNIRP has generally included a reduction factor of up to five in setting basic restrictions across the frequency range up to 300 GHz. NRPB has issued a consultation document on exposure guidelines for electromagnetic fields up to 300 GHz (NRPB, 2003). This follows a comprehensive review of the scientific basis for the guidelines. The adoption of ICNIRP guidelines for workers and the public is proposed.

The following is a summary of the ICNIRP exposure guidelines for reference with regard to the exposures considered in Chapter 2.

The ICNIRP guidelines on basic restrictions are summarised in Table B1. Theoretical dosimetric considerations enable the basic restrictions in terms of current density and specific (energy) absorption rate (SAR) to be related to the external field quantities of electric and magnetic field strength which, in the far-field, can be expressed in terms of power density. At frequencies above 10 GHz where energy absorption is essentially confined to the surface tissues, exposure is expressed in power density ($W\,m^{-2}$).

The simple assumptions used in deriving these external field strength levels result in conservative values for the reference levels implying that, if exceeded, further investigation is needed to demonstrate compliance with the basic restrictions. This is

the reason why apparent exposure above readily measured field strength levels is not in itself confirmatory evidence of non-compliance with the recommended basic restrictions but indicative of a need for more extensive exposure assessment.

The power density levels for frequencies above 10 GHz are given in Table B2 and the external field strength reference levels for occupational and public exposure are shown in Tables B3 and B4, respectively.

Exposure levels to which workers or the public could be exposed can be compared with the ICNIRP guideline reference levels. Examples of how exposure measurements relate to the appropriate guidelines are illustrated in Figures B1–B3.

TABLE B1 *ICNIRP basic restrictions for time-varying electric and magnetic fields for frequencies up to 10 GHz*

Exposure characteristics	Frequency range	Current density for head and trunk (mA m^{-2}) (rms)	Whole-body average SAR (W kg^{-1})	Localised SAR (head and trunk) (W kg^{-1})	Localised SAR (limbs) (W kg^{-1})
Occupational	Up to 1 Hz	40	–	–	–
	1–4 Hz	$40/f$	–	–	–
	4 Hz–1 kHz	10	–	–	–
	1–100 kHz	$f/100$	–	–	–
	100 kHz–10 MHz	$f/100$	0.4	10	20
	10 MHz–10 GHz	–	0.4	10	20
General public	Up to 1 Hz	8	–	–	–
	1–4 Hz	$8/f$	–	–	–
	4 Hz–1 kHz	2	–	–	–
	1–100 kHz	$f/500$	–	–	–
	100 kHz–10 MHz	$f/500$	0.08	2	4
	10 MHz–10 GHz	–	0.08	2	4

Notes

(a) f is the frequency in hertz.

(b) Because of electrical inhomogeneity of the body, current densities should be averaged over a cross-section of 1 cm^2 perpendicular to the current direction.

(c) For frequencies up to 100 kHz, peak current density values can be obtained by multiplying the rms value by $\sqrt{2}$ (~ 1.414). For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$.

(d) For frequencies up to 100 kHz and for pulsed magnetic fields, the maximum current density associated with the pulses can be calculated from the rise/fall times and the maximum rate of change of magnetic flux density. The induced current density can then be compared with the appropriate basic restriction.

(e) All SAR values are to be averaged over any 6-minute period.

(f) Localised SAR averaging mass is any 10 g of contiguous tissue; the maximum SAR so obtained should be the value used for the estimation of exposure.

(g) For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$. In addition, for pulsed exposures in the frequency range 0.3–10 GHz and for localised exposure of the head, in order to limit or avoid auditory effects caused by thermoelastic expansion, an additional basic restriction is recommended. This is that the specific absorption should not exceed 10 mJ kg^{-1} for workers and 2 mJ kg^{-1} for the general public, averaged over 10 g of tissue.

Exposure characteristics	Power density ($W\ m^{-2}$)
Occupational exposure	50
General public	10

TABLE B2 *ICNIRP basic restrictions for power density for frequencies between 10 and 300 GHz*

Notes

(a) Power densities are to be averaged over any 20 cm^2 of exposed area and any $68/f^{1.05}$-minute period (where f is in GHz) to compensate for progressively shorter penetration depth as frequency increases.

(b) Spatial maximum power densities, averaged over 1 cm^2, should not exceed 20 times the values above.

Frequency range	*E*-field strength ($V\ m^{-1}$)	*H*-field strength ($A\ m^{-1}$)	*B*-field (μT)	Equivalent plane wave power density, S_{eq} ($W\ m^{-2}$)
Up to 1 Hz	–	$1.63\ 10^5$	$2\ 10^5$	–
1–8 Hz	20 000	$1.63\ 10^5/f^2$	$2\ 10^5/f^2$	–
8–25 Hz	20 000	$2\ 10^4/f$	$2.5\ 10^4/f$	–
0.025–0.82 kHz	$500/f$	$20/f$	$25/f$	–
0.82–65 kHz	610	24.4	30.7	–
0.065–1 MHz	610	$1.6/f$	$2.0/f$	–
1–10 MHz	$610/f$	$1.6/f$	$2.0/f$	–
10–400 MHz	61	0.16	0.2	10
0.4–2 GHz	$3f^{½}$	$0.008f^{½}$	$0.01f^{½}$	$f/40$
2–300 GHz	137	0.36	0.45	50

TABLE B3 *ICNIRP reference levels for occupational exposure to time-varying electric and magnetic fields (unperturbed rms values)*

Notes

(a) f as indicated in the frequency range column.

(b) Provided that basic restrictions are met and adverse indirect effects can be excluded, field strength values can be exceeded.

(c) For frequencies between 100 kHz and 10 GHz, S_{eq}, E^2, H^2 and B^2, are to be averaged over any 6-minute period.

(d) For peak values at frequencies up to 100 kHz see Table B1, note (c).

(e) Between 100 kHz and 10 MHz, peak values for the field strengths are obtained by interpolation from the 1.5-fold peak at 100 kHz to the 32-fold peak at 10 MHz. For frequencies exceeding 10 MHz it is suggested that the peak equivalent plane wave power density, as averaged over the pulse width, does not exceed 1000 times the S_{eq} restrictions, or that the field strength does not exceed 32 times the field strength exposure levels given in the table.

(f) For frequencies exceeding 10 GHz, S_{eq}, E^2, H^2 and B^2 are to be averaged over any $68/f^{1.05}$-minute period (where f is in GHz).

(g) No *E*-field value is provided for frequencies < 1 Hz, which are effectively static electric fields. Electric shock from low impedance sources is prevented by established electrical safety procedures for such equipment.

TABLE B4 *ICNIRP reference levels for general public exposure to time-varying electric and magnetic fields (unperturbed rms values)*

Frequency range	*E*-field strength ($V\ m^{-1}$)	*H*-field strength ($A\ m^{-1}$)	*B*-field (μT)	Equivalent plane wave power density, S_{eq} ($W\ m^{-2}$)
Up to 1 Hz	–	$3.2\ 10^4$	$4\ 10^4$	–
1–8 Hz	10 000	$3.2\ 10^4/f^2$	$4\ 10^4/f^2$	–
8–25 Hz	10 000	$4000/f$	$5000/f$	–
0.025–0.8 kHz	$250/f$	$4/f$	$5/f$	–
0.8–3 kHz	$250/f$	5	6.25	–
3–150 kHz	87	5	6.25	–
0.15–1 MHz	87	$0.73/f$	$0.92/f$	–
1–10 MHz	$87/f^{½}$	$0.73/f$	$0.92/f$	–
10–400 MHz	28	0.073	0.092	2
0.4–2 GHz	$1.375f^{½}$	$0.0037f^{½}$	$0.0046f^{½}$	$f/200$
2–300 GHz	61	0.16	0.20	10

Notes

(a) f as indicated in the frequency range column.

(b) Provided that basic restrictions are met and adverse indirect effects can be excluded, field strength values can be exceeded.

(c) For frequencies between 100 kHz and 10 GHz, S_{eq}, E^2, H^2 and B^2, are to be averaged over any 6-minute period.

(d) For peak values at frequencies up to 100 kHz see Table B1, note (c).

(e) Between 100 kHz and 10 MHz, peak values for the field strengths are obtained by interpolation from the 1.5-fold peak at 100 kHz to the 32-fold peak at 10 MHz. For frequencies exceeding 10 MHz it is suggested that the peak equivalent plane wave power density, as averaged over the pulse width, does not exceed 1000 times the S_{eq} restrictions, or that the field strength does not exceed 32 times the field strength exposure levels given in the table.

(f) For frequencies exceeding 10 GHz, S_{eq}, E^2, H^2 and B^2 are to be averaged over any $68/f^{1.05}$-minute period (where f is in GHz).

(g) No *E*-field value is provided for frequencies < 1 Hz, which are effectively static electric fields. Perception of surface electric charges will not occur at field strengths less than $25\ kV\ m^{-1}$. Spark discharges causing stress or annoyance should be avoided.

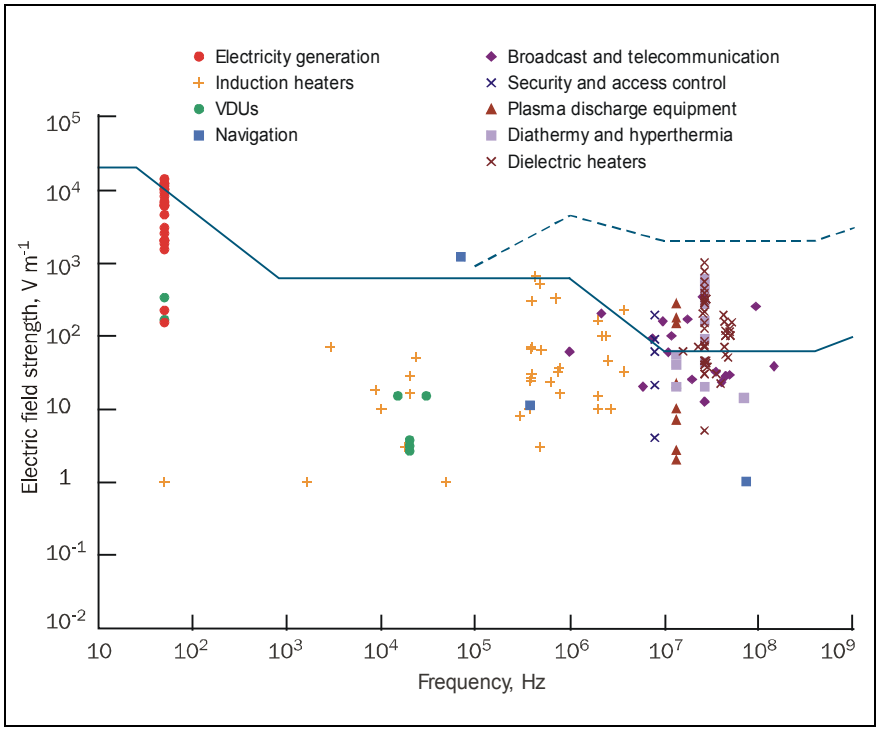

FIGURE B1
Examples of occupational electric field strength exposures to 1 GHz. The measured values are shown together with the ICNIRP reference levels for rms electric field strength (solid line) and peak electric field strength (broken line)

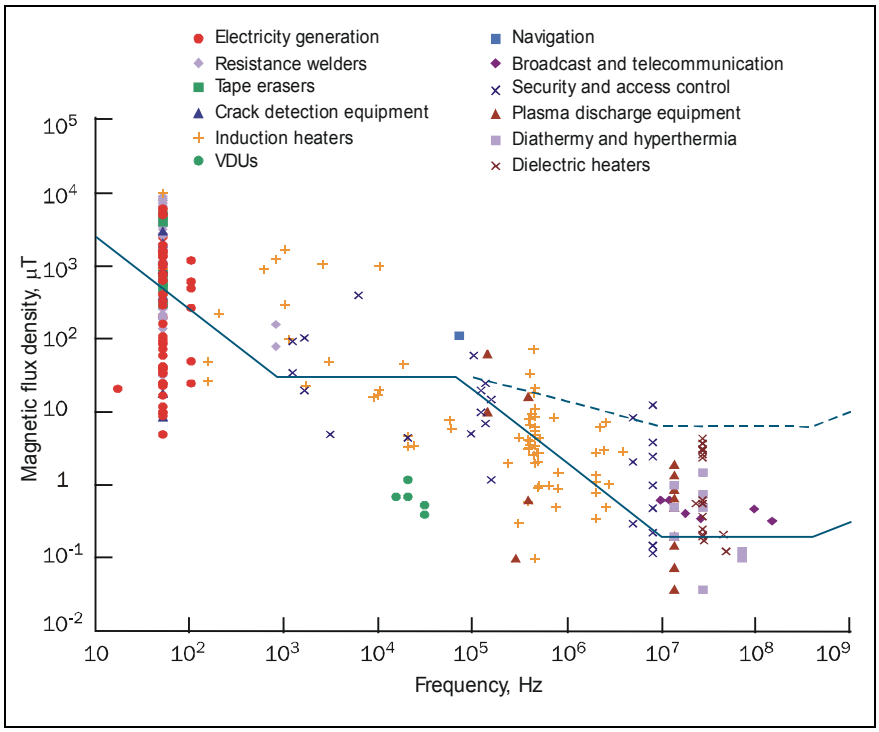

FIGURE B2
Examples of occupational magnetic field exposures to 1 GHz. The measured values are shown together with the ICNIRP reference levels for rms magnetic flux density (solid line) and peak magnetic flux density (broken line)

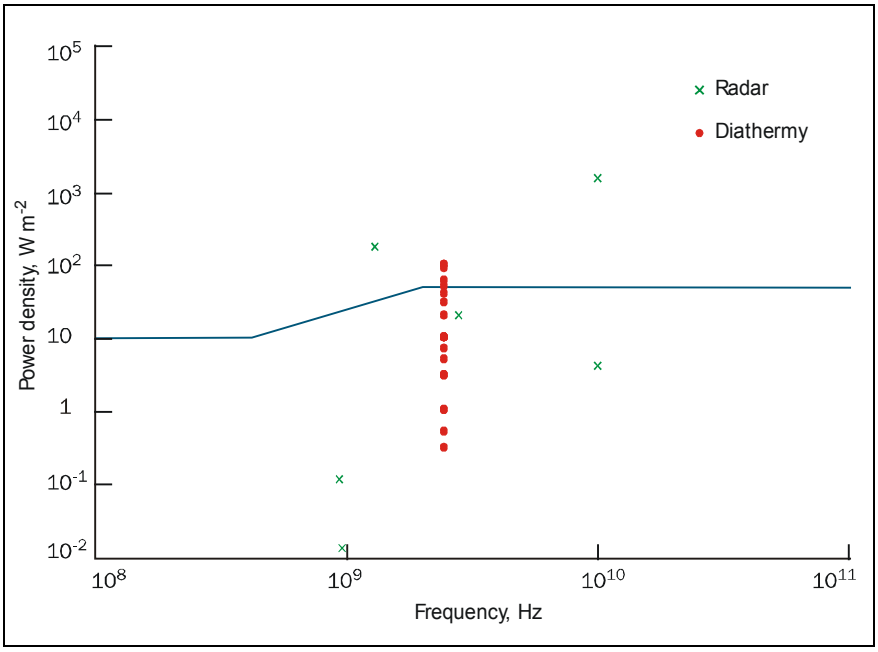

FIGURE B3
Occupational power density exposures to 100 GHz. Occupational magnetic field exposures are shown with the ICNIRP reference levels for rms magnetic flux density (solid line)

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Appendix C

UK RESEARCH

MOBILE TELECOMMUNICATIONS AND HEALTH RESEARCH PROGRAMME

The Mobile Telecommunications and Health Research (MTHR) Programme was established in February 2001 following the publication of a report in May 2000 by an Independent Expert Group on Mobile Phones (IEGMP), under the chairmanship of Sir William Stewart, entitled *Mobile Phones and Health*. Funds of £7.36 million have been allocated to the Programme, with government contributing half the funds and industry contributing the other half. The IEGMP report recognised the need for any such research to be demonstrably independent, and consequently arrangements have been put in place to separate the funding and scientific management of the Programme. The latter is carried out by an independent committee of research experts, chaired by Professor Lawrie Challis who was formerly vice-chairman of IEGMP.

Three calls for research proposals have attracted projects that cover both the areas of scientific uncertainty highlighted by the IEGMP report, and some additional areas of research that the Programme Management Committee has identified to be of highest importance and relevance. Eighteen research projects (see below) have been funded to date by the Programme Management Committee. In addition, the Department of Trade and Industry has directly funded a further three projects that were considered to be outside the scope of the main Programme. The Home Office has agreed to provide funding for projects on the TETRA emergency services radio system as an adjunct to the Programme (to date one project has been funded). Several of the projects funded under the Programme are now either complete or nearing completion. Third call applications are being considered at the moment. Further information on the MTHR and Home Office research programmes can be found on their websites at http://www.mthr.org.uk/ and http://www.homeoffice.gov.uk/docs/tetra.html.

Epidemiological studies

Case-control Study of Risk of Brain Tumours and Acoustic Neuroma in Relation to Use of Mobile Phones: South East England

Professor A J Swerdlow, Ms M Schoemaker and Dr R Houlston

Institute of Cancer Research

DURATION: FEBRUARY 2002 – JULY 2004

This project is a case–control study comparing mobile phone use and other radiofrequency radiation exposure and, in addition, other potentially confounding variables such as ionising radiation and genes, between cases (ie patients who have the study cancers) and controls (subjects who do not have these cancers). This project plans to recruit 1000 brain tumour and acoustic neuroma patients and 1000 controls in south east England. The brain tumour study will contribute to international combined analyses coordinated by the International Agency for Research on Cancer (the Interphone Project).

UK Case–control Study of Adult Brain Tumours

Dr P McKinney[*], Professor T Sorahan[†], Dr K Muir[‡] and Dr M Van Tongeran[†]
NHS Scotland[*], University of Birmingham[†] and University of Nottingham[‡]

DURATION: JANUARY 2002 – JUNE 2004

This is a population based case–control study. It is conducted by identifying newly diagnosed patients with brain tumours from four areas in England and Scotland. The patients (with permission) help the study by giving details of their past use of mobile phones, other information about their past occupations and medical histories and also donate a blood sample. People without brain tumours are chosen at random from the general population but to be of the same age, sex and residence as the patient group, and are asked for identical information. The information from patients is then contrasted with that for the public as a whole. This will help to ascertain, for example, if their past use of mobile phones is the same as, or different to, that of the general public. Other possible causes of brain tumours are examined in the same way. These other areas of interest include exposure to solvents, pesticides, head injuries and exposure to ionising radiation.

Cohort Study of Mobile Phone Users (Pilot Study)

Professor P Elliott[*], Dr L Jarup[†] and Professor A Ahlbom[‡]
Imperial College[*], Small Area Health Statistics Unit[†] and Karolinska Institute[‡]

DURATION: JANUARY 2002 – JUNE 2003

The initial part of the study is a one-year pilot investigation to establish the feasibility and methods for a large long-term ('cohort') study of the health effects of exposure to radiofrequency radiation from use of mobile phones. Because of the large cohort size envisaged for the main study, new methodology for collecting data using modern communications will need to be explored. Similarly, the exposures related to mobile telephony are notoriously difficult to study in epidemiological research. Therefore, novel procedures will be developed and evaluated. The overall purpose of the proposed study is to establish a cohort of phone users, to characterise long-term radiofrequency exposure of the cohort participants, to collect information on a range of health outcomes, and to examine these in relation to radio-frequency exposure.

Case–control Study of Risk of Leukaemia in Relation to Use of Mobile Phones

Professor A J Swerdlow[*], Professor M F Greaves[*] and Professor D C Linch[†]
Institute for Cancer Research[*] and UCL Medical School[†]

DURATION: MAY 2002 – APRIL 2007

The project is a case–control study comparing mobile phone use and other radiofrequency radiation exposure and, in addition, other potentially confounding variables such as ionising radiation and genes, between cases (ie patients who have the study cancers) and controls (subjects who do not have these cancers). The study plans to recruit 900 leukaemia patients and 900 controls, aged 18 to 59 years, in south east England.

Case–control Study of Cancer Incidence in Early Childhood and Proximity to Mobile Phone Base Stations

Professor P Elliott, Dr N G Best, Professor D Briggs and Dr M P Little

Imperial College

DURATION: APRIL 2003 – APRIL 2005

This study proposes to investigate risk of early childhood cancers – and, in particular, leukaemia and non-Hodgkin's lymphomas (NHL) – among the population residing near mobile phone base stations. A case–control approach will be used whereby the residential locations (with respect to mobile phone base stations) of children with cancer (cases) are compared to those without cancer (controls) in England and Wales. The rationale for this approach is several-fold: the IEGMP report made specific reference to childhood cancers, since children may be more susceptible with short latency, higher absorption (and early clinical effects); and young children (under five years old) are likely to spend most of their time in or near the home. In addition, there will be no direct exposure to mobile phones amongst this age group (in comparison with older children and other age groups).

Volunteer studies

Effects of Mobile Phone Radiation on Blood Pressure

Professor A T Barker[*], Dr P R Jackson[†], Dr G G Cook[†] and Dr L A Coulton[†]

Royal Hallamshire Hospital[*] and University of Sheffield[†]

DURATION: AUGUST 2002 – JANUARY 2006

The principal aim of this study is to determine whether the electromagnetic fields from mobile phones increase the blood pressure of a group of 100 normal volunteers. Subjects will receive five different types of electromagnetic exposure using the standard MTHR human exposure system (sham, carrier wave at GSM frequency, modulated GSM, carrier wave at TETRA frequency and modulated TETRA) during which their blood pressure and cardiac activity will be monitored. Blood samples will be analysed for catechols (which are markers of sympathetic nervous system activity). Twenty-four hour ambulatory blood pressure monitoring will be used to assess the duration of any effects.

Mobile Cellular Communication and Cognitive Functioning

Professor R Russo, Professor E Fox and Professor D Mirshekar

University of Essex

DURATION: MARCH 2002 – AUGUST 2004

A series of double-blind laboratory controlled experiments, conducted on adult volunteers, will assess the effect of concurrent exposure to radiofrequency electromagnetic fields emitted by the antenna of mobile phones on memory and attention. Radiofrequency signals will be generated in the laboratory using a signal source device covering the standard frequencies used by GSM mobile phones. The present research intends to overcome the limitations of previous studies providing a thorough evaluation of the impact of the use of GSM mobile phones on attention and memory in adults.

Effects of Mobile Phone Usage on Labyrinthine Function

Professor L Luxon[*], Dr B Ceranic[†], Dr R Cox[*] and Dr P Chadwick[‡]
National Hospital for Neurology and Neurosurgery[*], University College London[†] and MCL[‡]

DURATION: AUGUST 2002 – JANUARY 2004

Low level radiofrequency signals applied to one side of the head may produce vague symptoms of disorientation, headache and nausea as a result of stimulation of the balance receptors in the internal ear. This double-blind study will test at least 20 subjects who complain of specific symptoms, defined by a questionnaire, after prolonged mobile phone use (more than 15 minutes), and 20 people who have no such complaint. Each person will undergo a series of trials, in which a specially designed device is held, in a standard position, to each ear for 30 minutes in one of three different test modes. The device can be programmed to emit a pulsed or continuous radio-frequency emission or no emission and, in the active pulsed and continuous modes, will deliver the same mean power, on the same 900 MHz GSM operating frequency, and will mimic the output of a typical handset. Before and after each trial, sensitive tests of the hearing and balance receptors will be conducted to determine whether radiofrequency signals cause stimulation of the internal ear.

The ear and mode of operation of the device will be randomly selected for each trial by a computer program, such that neither the experimenter nor the subject is aware of the test mode for any particular trial. After each trial, the subject will be asked if the device was emitting signals to confirm whether or not he/she was blind to any test radio-frequency stimulation. At the end of the protocol, each subject will have undergone trials of all three test modes in each ear. The results of the hearing and balance tests will be compared between trials with and without pulsed emissions and with and without continuous emissions, between the ears of those subjects with only one symptomatic ear, for both pulsed and continuous stimulation, and between subjects complaining of symptoms and those with no complaint.

Effect of Mobile Phone Use on Symptoms and Neuroendocrine Function in 'Normal' and 'Hypersensitive' Users

Professor S Wessely, Dr A Cleare and Mr J Rubin
King's College London

DURATION: APRIL 2003 – APRIL 2006

This research will examine whether mobile phone signals cause unpleasant symptoms such as headaches, nausea, dizziness and fatigue. It will also investigate whether mobile phone signals affect the levels of certain hormones that are important in regulating metabolism. The study will involve placing a mobile phone next to the heads of volunteers. This phone will either be switched on or off, but has been adapted so that neither the volunteer nor the researcher will know which it is. While the phone is in position, several blood samples will be taken for testing and the volunteer will be asked to describe how he or she is feeling. A comparison will then be made between the results of sessions in which the phone was switched on and those in which the phone was switched off. This will be done with two different groups of volunteers: a group of people who do not normally experience any problems when using mobile phones, and a group of 'hypersensitive' people who often experience symptoms when

they use a mobile. Therefore, even if mobile phone signals are only a problem for a small proportion of the population, this study will still be able to detect this.

Conversations in Cars: The Relative Hazards of Mobiles Phones

Mr A Parkes[*] and Dr T C Lansdown[†]
Transportation Research Laboratory[*] and Heriot Watt University[†]

DURATION: DECEMBER 2001 – NOVEMBER 2002

The aim of this research is to measure the distraction from hands-free phones in relation to the other common driver distractions such as talking with passengers or tuning the radio. The TRL Driving Simulator will be used to provide a realistic driving task in a safe and controlled environment. Participants will be asked to drive as they would normally. In one part of the experiment a passenger will sit next to the driver and have a conversation. The experimenter's side of the conversation will follow a set script. The driver will also be asked to perform some common in-vehicle tasks (eg tuning the radio). In the second part the driver will have a similar conversation using a hands-free mobile phone. Driving performance will be compared across these different tasks to see which interferes most with safe driving.

Mechanistic studies

Effect of Pulsed Radiofrequency Electromagnetic Fields on Redox Signalling and Calcium Homeostasis

Dr M Bootman, Dr P Lipp and Mr R O'Connor
The Babraham Institute

DURATION: JANUARY 2002 – DECEMBER 2004

The group will use high-throughput screening technology, which is used by the pharmaceutical industry in drug discovery research. An automated cellular imaging system will be constructed that will allow the measurement of cellular fluorescence, while the cells are exposed to pulsed radiofrequency electromagnetic fields similar to those produced by mobile phones. This will permit real-time observation of signalling events that may occur when cells are exposed to radiofrequency fields. Mammalian tissues will be used, including neurons, glia, endothelium and smooth muscle, to cover a representative range of cell types that would be exposed during mobile phone use. The automation of the high-throughput imaging technology will permit a large number of samples to be processed and will minimise the possibility of experimental bias. Sophisticated software algorithms will then be used to extract information from the data to determine whether and where any signalling events are occurring.

Cellular and Subcellular Effects of Microwave Radiation in the Simple Model Nematode *Caenorhabditis Elegans*

Dr D de Pomerai and Dr D W Thomas
University of Nottingham

DURATION: APRIL 2002 – MARCH 2005

The group has previously reported that prolonged exposure to low intensity microwaves switches on the so-called stress response in nematodes. This is a general protective cellular response, which is also activated by heat and toxic chemicals; it provides a measure of the stress experienced by the test worms. Several aspects of this

work will be expanded during the MTHR-funded project. First, the group will determine which of the nematode's 19 000 genes are switched on or off during microwave exposure, and will carefully compare this pattern of gene-expression changes with that caused by mild heating. Second, the group will make use of the worm's excellent genetics to unravel the genetic pathway through which microwaves switch on stress-response genes. Third, temperature-sensitive mutant worm strains will be used to ask whether certain subcellular structures are more sensitive to microwaves. This question will also be examined by determining how microwaves interact with the worms across a range of different frequencies. Detailed modelling and field measurements of the exposure system will be used to rule out the possibility that a stress response might be activated simply by microwave heating. A wide variety of control strategies will be used to eliminate other possible artefacts.

Effects of Radiofrequency Radiation on Brain Physiology and Function

Dr Z J Sienkiewicz[*], Dr J Uney[†] and Dr J Tattersall[‡]

NRPB[*], Bristol University Centre for Neuroendocrinology[†] and Dstl Porton Down[‡]

DURATION: FEBRUARY 2002 – JANUARY 2005

The project will investigate if the radiofrequency signals used by mobile phones can affect the brain and alter the way it works. To achieve this, the project will look for changes in the molecular control of brain cells, changes in electrical activity within specific areas of the brain, and for changes in the performance of learning and memory tasks. This integrated study is not possible using people, and so will use mice. Since it is unclear which specific characteristics of the signal might be important in the causation of any biological effects, the project will use three frequencies (400, 900 or 2200 MHz) representing different transmission systems, a range of local absorbed energy rates in the head (2, 10 or 20 W kg^{-1}) and different exposure durations (1 hour single or repeated). All work with animals will be subject to ethical approval and be regulated under the Animals (Scientific Procedures) Act 1986.

Exposure and dosimetry

Measurement of the Dielectric Properties of Biological Tissue at Microwave Frequencies

Dr C Gabriel

MCL

DURATION: JANUARY 2002 – DECEMBER 2004

Detailed knowledge of the dielectric properties of biological tissues is essential if the interaction of electromagnetic radiation with the body is to be understood, quantified and interpreted. This project deals with the determination of the dielectric properties of human and animal tissues in the mobile telecommunications frequency range. The measurement programme is structured to provide the following information: (a) data on the dielectric properties of porcine tissues and an assessment of the expanded uncertainty of the measurement, (b) any systematic variation of the dielectric properties as a function of age, and (c) a study of the dielectric properties of skin on human volunteers. This project addresses the specific IEGMP recommendation for improved dosimetry and it will enable better assessment of exposure of children and adults to electromagnetic fields from telecommunications systems.

Interaction of Emerging Mobile Telecommunications Systems with the Human Body

Dr S Porter, Professor A Marvin and Dr M Capstick
University of York

DURATION: APRIL 2002 – MARCH 2005

The main aim of the project is to provide reliable, validated data on the electromagnetic field strengths and energy deposition within the human body associated with the use of current and future mobile telecommunications. This includes the development of techniques to determine human exposure to such systems. Different areas to be studied include handheld mobile phones, hands-free sets used with mobile phones, laptops with antennas built in, wearable PCs and base stations. The work will also develop reliable methods for the testing of such devices as listed above. The aim will be achieved by computer modelling and experiments. Computer models of humans and mobile phones will be developed for a range of situations where the devices listed above will be used. Physical models of humans will be constructed and used for the measurements. For both experiments and computer simulation, the techniques used will include analysis of the variability of mobile telecommunication devices and situations.

Assessment of Specific (Energy) Absorption Rate (SAR) in the Head from TETRA Handsets

Dr P J Dimbylow, Dr S M Mann, Dr R P Blackwell and Dr T G Cooper
NRPB

DURATION: MARCH 2002 – FEBRUARY 2003

It is proposed to calculate the distribution of power absorbed in an anatomically realistic model of the head from TETRA handsets. TETRA is a modern digital private mobile radio system designed to meet the requirements of professional users, such as the police and fire services. The handsets use a helical antenna, and it is important to experimentally verify the mathematical description of this antenna type. The study will be performed in two parts. A mathematical model of the helical antenna and TETRA handset will be produced. This model will be validated by comparing predicted field distributions close to the handset with experimentally measured values in the absence of the head. On successful completion of the first part, coupled head/handset calculations will be performed. The calculated power absorbed in the head will be compared with the basic restrictions from safety guidelines to assess compliance.

Traceability for Mobile Telecommunications and Health Research – Dosimetry in Support of the Programme

Mr R N Clarke[*], Mr B G Loader[*], Dr K Lees[*], Mr A P Gregory[*], Dr M J Hall[*], Mr S Harmon[*] and Professor A W Preece[†]
National Physical Laboratory[*] and University of Bristol[†]

DURATION: DECEMBER 2001 – END OF PROGRAMME

Consultancy on measurement and dosimetry will cover advice given to the Programme Management Committee on measurement and standards, advice on good practice to individual laboratories and contributions to workshops on measurement and uncertainty estimation. Where appropriate, NPL will be providing traceable calibrations of microwave parameters to the MTHR Programme in support of dosimetry studies. These will typically include calibrations of field strength and SAR sensors and of antenna and

dielectric parameters. Calibrations will be undertaken in accordance with established NPL measurement practices.

Traceability for Mobile Telecommunications and Health Research – Measurement of Magnetic Emissions from Commercial Mobile Phones

Mr R N Clarke[*], *Mr B G Loader*[*], *Dr K Lees*[*], *Mr A P Gregory*[*], *Dr M J Hall*[*], *Mr S Harmon*[*] *and Professor A W Preece*[†]
National Physical Laboratory[*] *and University of Bristol*[†]

DURATION: DECEMBER 2001 – JUNE 2003

The very low frequency magnetic field studies will employ both national standard facilities and calibrated flux-gate magnetometer measurements of pulsed and continuous magnetic emissions from commercial mobile phones, including GSM and TETRA devices.

PROJECTS FUNDED BY DTI AS AN ADJUNCT TO THE PROGRAMME

SAR Testing of Hands-free Mobile Phones

Dr S Porter
University of York

DURATION: JULY 2002 – JANUARY 2003

The main aim of the project is to estimate the likely differences in exposure between using a mobile phone in normal mode and when used in conjunction with a hands-free kit. This includes the likely differences in the measured exposure under standard test conditions (using the standard head phantom) when a mobile phone is used with and without a hands-free kit; the likely effects upon these measured results of incorporating a representative body phantom in the exposure measurements; estimates of the induced currents on the cabling of hands-free kits with and without the presence of a phantom torso to aid in deducing the effects of omitting the torso from SAR tests. The aim will be achieved through measurements and numerical modelling. Numerical phantoms and models will be developed for a range of exposure scenarios. A compliant SAR test system will be used for exposure measurements. The techniques employed will include finite-difference time domain and moment method modelling, sensitivity analysis, error analysis and exposure measurements. The main outputs will include: exposure assessments for a range of scenarios both with and without hands-free kits and with and without torso phantoms; an enhanced understanding of the factors which affect the measured SAR when using hands-free kits; recommendations for appropriate test scenarios for best assessment of SAR related to use of hands-free kit.

International EMF Dosimetry Project

Dr P Chadwick
MCL

DURATION: FEBRUARY 2002 – JANUARY 2005

The International EMF Dosimetry Project was initiated at a NATO Advanced Research Workshop on Radiofrequency Dosimetry in Slovenia in 1998. The mission of the project is to promote and develop high quality electromagnetic field dosimetry for the assessment of human exposure and for *in vitro* and *in vivo* experimental systems.

The intention is to create an internationally accepted Dosimetry Handbook which will be a living and substantially on-line document with integrated software tools and guides for dosimetry measurement and calculation. The Handbook will be assembled from the contributions of international experts in all aspects of electromagnetic field dosimetry. The primary benefactor of this project would be public health, via assurance of the quality and transportability of human and experimental dosimetry; the ability to acquire robust scientific information depends on accurate and precise dosimetry. The Handbook will be a key tool in the international harmonisation of guidelines and standards for human exposure to electromagnetic fields. The project will promote commonality of dosimetry by making the highest quality dosimetric tools available universally. Many of the differences between exposure guidelines reflect differences in dosimetry rather than underlying philosophy. Promoting the convergence of dosimetry should encourage the convergence of electromagnetic field guidelines. The project addresses the specific IEGMP recommendation for improvements in dosimetry and, in particular, dosimetry for pulsed and ultra-wide band communications sources. The development of UK dosimetry expertise and the encouragement of the 'next generation' of researchers are specific additional objectives.

Measurement of the Power Density of Radio Waves in the Vicinity of Microcell and Picocell Base Stations

Dr S M Mann and Dr T G Cooper

NRPB

DURATION: JANUARY 2002 – JUNE 2003

Radio wave strengths will be measured near microcell and picocell base stations at 20 sites with a range of different base station designs and site characteristics in order to assess typical exposure levels. Spot measurements will be made using a spectrum analyser and broadband antennas over a wide range of frequencies, chosen to encompass other environmental radio transmitters as well as base stations. A structured series of measurements will be made to produce a detailed profile of the radio wave strengths at ground level at a subset of the sites. The measurements will be interpreted by comparing them with the reference level advised by ICNIRP for exposure of the general public and also by comparing them with previously published measurements from larger (macrocell) base stations.

PROJECTS FUNDED BY THE HOME OFFICE AS AN ADJUNCT TO THE PROGRAMME

Detection of Effects of Microwave Radiation on the Electrical Activity of the Brain

Dr S Butler and Professor A W Preece

Burden Neurological Institute

DURATION: JULY 2003 – JANUARY 2005

This group was the first to report an effect of radiation from mobile phones on human behaviour: reaction time was speeded up in the performance of a task that depended on parts of the brain closest to the aerial. A number of studies have since confirmed this finding and reported other beneficial effects including improved

memory and attention. These phenomena are unexpected. The only known effect of microwave radiation on the brain is to raise its temperature and the emissions from mobile phones are restricted to a level that has a negligible effect on brain temperature. This study is designed to find out what microwave radiation is doing to the brain to cause the observed effects on behaviour.

The electrical activity of the brain will be recorded (from electrodes on the scalp) while volunteer subjects experience visual and auditory stimuli and undertake a number of mental tasks. At the same time they will be exposed to transmissions from a TETRA handset. TETRA is the new mobile telecommunications system for the public services which, like GSM mobile phones, relies upon microwave radiation. The recordings should reveal any changes in the way the brain processes sensory inputs or in the electrophysiological activity underlying cognitive processes. In addition, the study will look at whether bursts of microwave radiation alter the timing of nerve impulses in the brain. If bursts of radiation reduce reaction time by synchronising the discharge of action potentials in the cerebral cortex, they will evoke electrical potentials that can be detected in recordings from the scalp.

Glossary

The descriptions below are intended to help the reader understand the text; they are not necessarily definitive scientific terms, for which the reader is advised to consult specialist sources.

Words in bold are defined separately.

TERMS ASSOCIATED WITH ELECTROMAGNETIC FIELDS

Analogue Original **cellular** technology used in the transmission of speech by Vodafone and Cellnet since 1985, operating as an analogue system at 900 MHz. Typically accessed by high powered phones installed in cars.

AM Amplitude modulation.

Action potential Voltage produced across a nerve cell membrane by a stimulus. It arises from the entry of sodium ions across the cell membrane, which results in membrane depolarisation.

Antenna Device designed to radiate or receive electromagnetic energy.

APC Adaptive Power Control. System used to control mobile phones and base stations in order to ensure that the radiated power does not exceed the minimum consistent with high quality communication. The system effectively operates to reduce average radiated powers.

Base station Facility providing transmission and reception for radio systems. For macrocells, the infrastructure comprises either roof- or mast-mounted antennas and an equipment cabinet or container. For smaller microcells and picocells, the antennas and other equipment may be housed in a single unit.

CDMA Code Division Multiple Access. System that encodes signals to a number of users, so that all of these users can simultaneously use a single, wide frequency band. Each user's handset decodes the information for that user, but cannot access information for any other user.

Cell/cellular A 'cell' in the context of mobile phone technology is the area of geographical coverage from a radio base station. 'Cellular' describes such systems, but is often used to distinguish the original analogue systems from the later digital **PCN** systems, although the latter themselves have cells.

CW Continuous wave.

Decibel (dB) A measure of the increase or decrease in power, P, at two points expressed in logarithmic form. Gain $= 10 \log_{10}(P_2/P_1)$.

DECT Digital Enhanced Cordless Telecommunications.

Dielectric A class of materials that act as electric insulators.

Digital Technology introduced in the 1990s as a method of transmitting speech and data. Offers increased security, and technical advantages with low powered phones.

Dosimetry Measurement of the absorbed dose or dose rate by an object, as in a **radiofrequency** field.

DTX Discontinuous transmission. System regulating mobile phones to ensure that transmission occurs only during speech. The system has the effect of reducing the time of exposure to approximately half (assuming an equal conversation).

Effective radiated power (ERP) Power supplied to the antenna multiplied by the gain of the antenna in that direction relative to a half-wave dipole.

EIRP Equivalent isotropically radiated power. This is the power that would have to be emitted in *all directions* to produce a particular intensity and so takes account of the transmitter power plus the characteristics of the antenna.

Electric field Produces a force on a charged object (unit V m^{-1}).

Electric field strength (E) Force on a stationary unit positive charge at a point in an electric field. The magnitude of the electric field vector (unit V m^{-1}).

Electromagnetic fields Electric and magnetic fields associated with electromagnetic radiation.

Electromagnetic radiation A wave of electric and magnetic energy that travels or *radiates* from a source.

EMF Electromagnetic field.

FDD Frequency Division Duplex.

Frequency Number of complete cycles of an electromagnetic wave in a second (unit **hertz, Hz**).

GSM Global System for Mobile Telecommunications. An international operating standard for digital cellular mobile telecommunications. Enables mobile phones to be used across national boundaries. **PCN** operators work to the same standard but at different frequency allocations.

Harmonics Multiples of the fundamental frequency used for a particular source, eg 50 Hz harmonics are 100 Hz, 150 Hz, 200 Hz, etc.

Helmholtz coils Arrangement of two current carrying coils to produce a uniform magnetic field distribution between the coils.

Hertz (Hz) Unit of frequency. One cycle per second.

Impedance (of free space) Ratio of electric to magnetic field strength of an electromagnetic wave. In free space the value is 377 Ω.

IMT - 2000 International Mobile Telecommunications - 2000. International name for **UMTS**.

Infrared radiation **Electromagnetic radiation** capable of producing the sensation of heat and found between visible radiation and **radiofrequency radiation** in the electromagnetic spectrum.

Intensity Power crossing unit area normal to the direction of wave propagation (unit watts per square metre, W m^{-2}). See also **power density**.

Iridium Global, satellite based mobile phone system.

Isotropic (radiator) Having the same properties in all directions.

Magnetic field (B) Produces a force on a charged object moving at an angle to it (unit tesla, T). (See also **magnetic flux density**.)

Magnetic field strength (H) Related to **magnetic flux density**, *B*, through the permeability, μ, according to $B = \mu H$ (unit A m^{-1}).

Magnetic flux density Produces a force on a charged object moving at an angle to it (unit tesla, T). (See also **magnetic field.**)

Magnetite Naturally occurring oxide of iron with magnetic properties.

Microwave Electromagnetic radiation of ultra-high frequencies between 1 GHz and 300 GHz.

Order of magnitude Quantity given to the nearest power of ten. A factor of ten or so.

OFTEL Office of Telecommunications.

PCN Personal Communications Network. A mobile system principally directed towards the hand-portable, domestic user market and operating with **digital** technology at 1.8 GHz. The two main UK operators are One 2 One and Orange.

Permeability (μ) Quantity which, when multiplied by the **magnetic field strength**, gives the magnetic flux density. It indicates the degree of magnetisation in a medium when a magnetic field is applied.

Permittivity (ε) Quantity which, when multiplied by the **electric field strength**, gives the electric flux density. It indicates the degree of electric polarisation in a medium when an electric field is applied.

Plane wave A wave such that the corresponding physical quantities are uniform in any plane perpendicular to a fixed direction.

Power density Power crossing unit area normal to the direction of wave propagation (unit watts per square metre, $W\,m^{-2}$). See also **intensity**.

Power (flux) density (S) Power crossing unit area normal to the direction of wave propagation.

Poynting vector A vector, the flux of which through any surface represents the instantaneous electromagnetic power transmitted through this surface (synonymous with power flux density).

Radiofrequency (RF) Electromagnetic radiation used for telecommunications and found in the electromagnetic spectrum at longer wavelengths than **infrared radiation** (see Figure 2.1).

Root mean square (RMS) Certain electrical effects are proportional to the square root of the mean value of the square of a periodic function; this is known as the effective value or root mean square value.

Specific (energy) absorption rate, SAR Rate at which energy is absorbed by unit mass of tissue in an electromagnetic field (unit watts per kilogram, $W\,kg^{-1}$).

Third generation Next evolution of mobile phone technology, based on **UMTS** and expected to result in widespread use of video phones and access to multimedia information.

TDD Time Division Duplex.

TDMA Time division multiple access. System that divides each frequency band into a number of time slots, each allocated to a single user. Allows several users to operate on the same frequency at the same time.

TETRA Terrestrial trunk radio system.

UMTS Universal Mobile Telecommunications System.

Wavelength (λ) Distance between two successive points of a periodic wave in the direction of propagation, in which the oscillation has the same phase (unit metre, m).

Quantities and units used to characterise electromagnetic radiation

Quantity	Unit	Symbol
Frequency	hertz	Hz
Wavelength	metre	m
Electric field strength	volt per metre	$V\,m^{-1}$
Magnetic field strength*	ampere per metre	$A\,m^{-1}$
Magnetic field, B/magnetic flux density*	tesla	T
Intensity/power density	watt per square metre	$W\,m^{-2}$
Specific (energy) absorption rate (SAR)	watt per kilogram	$W\,kg^{-1}$

*A magnetic field strength of $1\,A\,m^{-1}$ is equivalent to a magnetic field of $4\pi\,10^{-7}\,T$ in non-magnetic media.

TERMS ASSOCIATED WITH EPIDEMIOLOGY AND EXPERIMENTAL BIOLOGY

Bias Any process at any stage of inference which tends to produce results or conclusions that differ systematically from the truth.

Case–control study An investigation into the extent to which a group of persons with a specific disease (the cases) and comparable persons who do not have the disease (the controls) differ with respect to exposure to putative risk factors.

Chi-square (χ^2) statistic A statistic to test for any association between disease risk and a measure of exposure. For a case–control study, this is based on the classification of cases and controls by level of exposure. To test for any association, the statistic should be compared with the χ^2 distribution on the appropriate number of degrees of freedom.

Chromosomes Rod-shaped bodies found in the **nucleus** of cells in the body. They contain the genes or hereditary material. Human beings possess 23 pairs.

Cohort study An investigation involving the identification of a group of individuals (the cohort) about whom certain exposure information is collected, and the ascertainment of occurrence of diseases at later times. For each individual, information on prior exposure can be related to subsequent disease experience.

Confidence interval (CI) An interval calculated from data when making inferences about an unknown parameter. In hypothetical repetitions of the study, the interval will include the parameter in question on a specified percentage of occasions (eg 90% for a 90% confidence interval).

Confounder A factor that is correlated with the exposure of interest and, independently, is related to the disease under investigation.

Degrees of freedom (df) Number of independent comparisons that can be made between the members of a sample. This important concept in statistical testing cannot be defined briefly. It refers to the number of independent contributions to a sampling distribution (such as χ^2, t, and F distribution). In a contingency table it is one less than the number of row categories multiplied by one less than the number of column categories.

Discordant pair A pairing of a diseased case and a matched control for which the case and the control differ in their exposure to a given factor.

DNA Deoxyribonucleic acid. The compound that controls the structure and function of cells and is the material of inheritance.

EEG Electroencephalogram. Measurement of changing voltages associated with brain activity.

Genes Biological units of heredity. They are arranged along the length of **chromosomes**.

Gene expression The realisation of genetic information encoded in **genes** to produce functional protein or **RNA**.

Ion Electrically charged atom or group of atoms.

Ion channel (gate) Protein that allows the passage of ions across a membrane, down a concentration gradient.

Ion pump A protein pump that moves ions across a membrane against a concentration gradient.

Matched odds ratio **Odds ratio** calculated on the basis of the comparison of cases and controls that are matched with respect to potential confounding factors.

Molecule Smallest portion of a substance that can exist by itself and retain the properties of the substance.

Mutation Chemical change in the **DNA** in the nucleus of a cell. Mutations in sperm or egg cells, or their precursors, may lead to inherited effects in children. Mutations in body cells may lead to effects in the individual.

Neurasthenic A term that has been used to describe collectively a range of symptoms that may occur in relation to real or perceived toxic exposures such as headache, fatigue, difficulty with memory, difficulty with concentration.

Neuron(e) Nerve cell. Basic unit of the nervous system, specialised for the transmission of electrical impulses.

Nucleus Controlling centre of higher cells. Contains the important material **DNA**.

Odds ratio Ratio of the odds of disease occurrence in a group with exposure to a factor to that in an unexposed group: within each group, the odds are the ratio of the numbers of diseased and non-diseased individuals.

One-sided test A test for a difference in only one direction (eg a test for an increased – but not a decreased – risk in an exposed group relative to a comparison group).

Prevalence ratio Ratio of the prevalence rates for the disease or symptoms under investigation in the study and comparison groups.

Probability value Probability that a test statistic would be as extreme as or more extreme than observed if the null hypothesis were true. The letter p, followed by the abbreviation ns (not significant) or by the symbol < (less than) and a decimal notation such as 0.01 or 0.05, is a statement of the probability that the difference observed could have occurred by chance under the null hypothesis.

Proportional mortality ratio (PMR) Ratio of the fraction of deaths due to a particular cause in a cohort to the corresponding fraction in a general population, adjusted with respect to age (and sex if relevant) on the basis of the distribution of deaths from all causes in the cohort. PMR is often expressed as a percentage, ie a PMR of 100 indicates that proportionate mortality is the same in the cohort and the general population.

Proportional registration ratio (PRR) Analogous to the proportional mortality ratio (PMR) but based on cancer registrations rather than deaths.

Relative risk Ratio of the disease rate in the group under study to that in a comparison group, with adjustment for confounding factors such as age, if necessary.

Risk Probability or likelihood of injury, harm or damage occurring.

RNA Ribonucleic acid.

Significance level Probability of obtaining a result at least as extreme as that observed in the absence of a raised risk. A result that would arise less than 1 in 20 times in the absence of an underlying effect is often referred to as being 'statistically significant'.

Standardised incidence ratio (SIR) Ratio (x 100) of the number of incident cancers in a group to the number expected in the general population with the same mixture of ages and sexes and interval of follow-up. Therefore an SIR of 100 signifies no raised risk; an SIR of more than 100 signifies a raised risk.

Standardised mortality ratio (SMR) The ratio of the observed number of deaths from a given cause in a cohort to that expected on the basis of both mortality rates for a general population and the age (and, if relevant, sex) distribution of person-years for the cohort. SMR is often expressed as a percentage, ie an SMR of 100 indicates that the age-adjusted mortality rate is the same in the cohort and the general population.

Statistical power Probability that, with a specified degree of confidence, an underlying effect of a given magnitude will be detected in a study.

Synergism Combined effect of two or more interacting agents that is greater than the addition of the single agent effects with known dose–effect relationships.

Transcription Synthesis of **RNA** from **DNA**.