Occupational Exposure to Electromagnetic Fields at Radio Transmitter Sites

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ABSTRACT

Exposures to radiofrequency electromagnetic fields and radiation have been assessed in order to investigate the range of exposures encountered by workers in the broadcast, telecommunications and air traffic control industries. The strengths of electric and magnetic fields have been measured at a number of sites transmitting a broad range of frequencies.

Equipment has been developed and employed for measuring and recording parameters associated with radiofrequency exposure. A meter for measuring radiofrequency limb current was developed and two generations of a data logger were produced. The data loggers were designed to record measurements of electric and magnetic field strength when used in conjunction with a commercially available personal exposure monitor. The combined monitor and logger resulted in an instrument with potential for use in epidemiological studies of occupational exposure to radiofrequency fields.

The response of the personal exposure monitor to incident fields when worn on the body has been investigated theoretically. Inter-comparisons of body-worn and hand-held instrumentation have been conducted at different types of transmitter site.

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EXECUTIVE SUMMARY

There is considerable interest in epidemiological studies of possible health effects arising from occupational exposure to radiofrequency electromagnetic fields and radiation. Epidemiological studies rely on estimates of exposure and these may be based on spot measurements or, preferably, on measurements of individual personal exposure logged over time.

Measurements of electric and magnetic field strength and limb current have been conducted in order to investigate the range of exposures encountered by workers in the broadcast, telecommunications and air traffic control industries. Electric and magnetic field strengths were measured using commercial portable survey equipment at a number of sites that transmitted a broad range of frequencies. Limb current was measured using a new lightweight instrument that was sensitive to frequencies up to 250 MHz.

Data loggers have been developed to record measurements of electric and magnetic field strength when used in conjunction with a commercially available personal exposure monitor. The combined monitor and logger resulted in an instrument with potential for use in epidemiological studies of occupational exposure to radiofrequency fields. The response of the personal exposure monitor to incident fields when worn on the body has been investigated theoretically.

Electric fields have been investigated at several sites using both portable survey equipment and personal exposure monitors. The electric field strengths measured using the two types of equipment generally agreed to within manufacturers' specified uncertainties when the user was facing towards the source of exposure, providing the measurement location was not in a region where the spatial distribution of the field was highly non-uniform.

To Dr Tim Cooper (1969-2006)

For Julie, Emily and Danny

The principal author of this report, Dr Tim Cooper of the Electromagnetic Fields Dosimetry Group of the Radiological Protection Division, died on 17 August 2006.

Tim will be remembered by his colleagues for his intellect, unstinting industry and exemplary scientific skills. His contribution to the measurement aspects of this study will be recalled by all who participated in it and his legacy of publications and wider contribution to the experimental dosimetry work of the Division provide testimony to his scientific work.

He will be missed more so for his imperturbable good nature and his willingness to bestow the benefits of his knowledge and experience on others.

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1 INTRODUCTION

Concerns over the possible health effects of exposure to radiofrequency (RF) electromagnetic fields and radiation have given rise to many epidemiological studies in recent years. The epidemiological and other evidence for possible health effects has been considered in a number of reviews (NRPB, 2004b; Sienkiewicz and Kowalczuk, 2005) and the shortcomings of previous studies have been examined. Several reviews have recommended further epidemiological research in populations exposed occupationally (AGNIR, 1992, 2003; Repacholi, 1998; RSC, 1999; IEGMP, 2000).

Many epidemiological studies that have investigated occupational exposures to RF fields have suffered from poor exposure assessment (IEGMP, 2000; Elwood, 2003; Ahlbom *et al*, 2004; NRPB, 2004a). In 1999, the Royal Society of Canada (RSC, 1999) concluded that exposure assessment was the greatest limitation to the interpretation of the epidemiological studies published to date. In the UK, improved studies of 'occupational groups for whom measurements show that there is genuinely a substantially raised exposure to RF fields' have been recommended by an Advisory Group on Non-ionising Radiation (AGNIR, 2003). The Group specified a key requirement of 'improved exposure measurements (or improved estimation of exposure) for individuals, or at least for occupational groups'.

In recommending studies involving highly exposed occupational groups, Repacholi (1998) stated that 'the identification of these groups would benefit from the development of individual RF dosemeters'. The Standing Committee on Epidemiology of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) has also noted that a key element in improving future epidemiological studies 'would be the use of a meter that monitors individual exposure' (Ahlbom *et al*, 2004). The development of a personal RF meter that can be used in large-scale epidemiological research has also been recommended by the Swedish Radiation Protection Authority (SSI, 2003).

A collaborative study has been carried out by the Radiation Protection Division of HPA (formerly the National Radiological Protection Board) and the Institute of Occupational Health (IOH), University of Birmingham to investigate the feasibility of an epidemiological study of the health effects of RF fields and radiation amongst workers in the UK. Part of the study involved investigating electric and magnetic fields and body currents at sites used for broadcast, telecommunications and air traffic control to determine the range of field strengths and induced currents likely to be encountered by personnel. Another important aspect of the study was the development of instrumentation with data-logging facilities for assessing real-time personal exposure to RF fields.

The next section describes the instrumentation used for measuring RF electric and magnetic field strength and current induced in the body. Section 3 gives the results of spot measurements of electric and magnetic field strength and induced current. Section 4 describes the personal exposure system developed for the study, and its evaluation is detailed in Section 5. The results of personal exposure measurements and analysis with a view to assessing possible exposure metrics for epidemiological studies are reported elsewhere (Cooper *et al*, 2004).

2 MEASUREMENT INSTRUMENTATION

For the purposes of this work, the term 'radiofrequency' applies to electromagnetic fields and radiation with frequencies between 3 kHz and 300 GHz. The radio spectrum, together with some lower frequencies, has been divided into ten bands by the International Telecommunication Union (ITU, 2000). Each band is a decade wide and the ITU nomenclature is given in Table 1.

TABLE 1 ITU frequency bands for the radio spectrum

Band	Abbreviation	Frequency range
Extra high frequency	EHF	30–300 GHz
Super high frequency	SHF	3–30 GHz
Ultra high frequency	UHF	300–3000 MHz
Very high frequency	VHF	30–300 MHz
High frequency	HF	3–30 MHz
Medium frequency	MF	300–3000 kHz
Low frequency	LF	30–300 kHz
Very low frequency	VLF	3–30 kHz
Voice frequency	VF	300–3000 Hz
Extremely low frequency	ELF	30–300 Hz

Sites hosting a variety of RF transmitters have been visited to allow spot measurements of electric and magnetic field strength and body current, in order to determine typical levels of exposure of workers. The field strength measurements were made using portable broadband RF survey meters and narrowband instrumentation. Limb current was measured using a transformer clamp connected to a current meter. The instrumentation and methods of use employed during the site visits are described below.

2.1 Portable survey instrumentation

2.1.1 Principles of operation

Portable RF measurement instrumentation, also known as hazard survey meters, provides a relatively simple and convenient means for measuring electric and magnetic field strength. This type of equipment is often used for assessing compliance with exposure guidelines, such as those published by ICNIRP (1999) and the Institute of Electrical and Electronics Engineers (IEEE, 1999). The desired characteristics of the meters, the principles of operation of different types of probe and calibration methods have been described in the literature (IEEE, 1991; NCRP, 1993; FCC, 1997a), hence the following summary will be brief.

Most commercially available RF survey instruments are broadband devices and contain the following four elements.

a Antenna (sensor)
b Detector
c Processing electronics
d Display device

The first two elements are generally contained within a hand-held probe which is connected to a meter, containing the processing electronics and display device, either directly or via a flexible lead. The lead may contain high-impedance or fibre-optic cables in order to minimise perturbation of the field being measured. The antenna in an electric field probe usually consists of one or more electric dipoles. Isotropic probes contain three mutually orthogonal dipoles and a vector summation is performed on their outputs in order to give a response that is independent of probe orientation. The antennas in magnetic field probes are usually loops or coils and three mutually orthogonal elements are required for an isotropic response.

The physical dimensions of the antenna elements are generally small compared with the wavelength corresponding to the highest frequency specified for the probe in order to optimise the uniformity of the frequency response. Small antennas also have the advantages that field perturbation is minimised and variations over a small region of space can be measured.

Two types of detector are commonly used in probes and these are diodes and thermocouples. Diodes are widely used since they are sensitive and can also tolerate relatively high field strengths without suffering overload. Diodes are non-linear devices and in weak fields they produce a rectified voltage proportional to the square of the incident field strength. In stronger fields, diodes operate out of the square-law region and processing electronics are required to compensate for the deviation. This can introduce imprecision in multiple-frequency environments and can affect the accuracy of measurements of time-averaged field strength when the fields are pulse modulated. Another potential source of error is the sensitivity of diodes to temperature variation. Diodes must be enclosed by optically opaque material in order to avoid photovoltaic effects.

Thermocouples detect temperature changes and produce a rectified voltage proportional to the power deposited in the junctions of the device. Since RF power is proportional to the square of field strength, thermocouples operate as true square-law devices in RF fields. This characteristic means thermocouple detectors are well adapted for measurements under conditions of multiple frequency and for evaluating the time-averaged strength of pulsed fields. Disadvantages of thermocouples include thermal drift, limited dynamic range, susceptibility to burnout in strong fields and their relative insensitivity.

A number of methods are used for calibrating RF survey probes. These may involve calibrating the probe under free-field plane-wave conditions or placing the probe inside a uniform field generated by, eg a rectangular waveguide, TEM cell or, in the case of magnetic field probes, Helmholtz coils. All of the methods may involve a transfer standard whereby the field strength is first measured using a standard probe, with known calibration, and then measured with the uncalibrated probe. The accuracy achieved in a calibration facility is rarely reproduced in practical measurements outside the laboratory because of the following reasons.

a The calibration is usually performed under plane-wave or uniform-field conditions, however the probe may respond differently under realistic conditions where exposure may be in the near field such that the field strength varies considerably over space. In the reactive near field the probe may couple with the radiator and alter its emission characteristics.

b In some calibrations the probe alone is immersed in the field, however in realistic situations the connecting lead and display unit are also positioned in the field.

c Measurements may be performed in the vicinity of dielectric or metallic scatterers and/or reflecting surfaces.

d In calibrations the probe is positioned in a mount designed for minimum perturbation of the incident field. During exposure assessments the probe is generally held by an individual whose body may couple to the antenna or act as a scattering object.

2.1.2 Portable survey equipment employed in the study

Several commercially available RF survey meters were used to measure electric and magnetic field strength during visits to broadcast, telecommunications and air traffic control sites. A list of the meters used and some of their technical specifications is given in Table 2. Meters that display power density have had their dynamic range converted to field strength in order to aid comparison. Some meters provided by the companies sponsoring the study were used at certain sites in addition to the meters compiled in the table.

TABLE 2 Portable survey meters used during site visits

Meter	Probe (where separate)	Electric or magnetic fields (E/H)?	Frequency range	Dynamic range
Aeritalia TE307	RV 19	E	20 Hz – 100 kHz	0.01–10 kV m^{-1}
Holaday HI-3003	STE-03	E	500 kHz – 6 GHz	22–1000 V m^{-1}
	CH	H	5–300 MHz	0.07–10 A m^{-1}
	LFH-02	H	500 kHz – 10 MHz	0.2–32 A m^{-1}
Holaday HI-4417		E	10 kHz – 1 GHz	1–300 V m^{-1}
Narda 8712	8721	E	300 MHz – 40 GHz	6–274 V m^{-1}
	8733D	H	10–300 MHz	0.5–1.6 A m^{-1}
	8761D	E	300 kHz – 3 GHz	6–274 V m^{-1}
	8781	E	2–18 GHz	9–274 V m^{-1}
Narda 8716	8721	E	300 MHz – 40 GHz	6–274 V m^{-1}
	8754	H	300 kHz – 10 MHz	0.2–7 A m^{-1}
Narda 8718	8721	E	300 MHz – 40 GHz	6–274 V m^{-1}
Radians Innova BMM-5		H	2–400 kHz	0.08–1600 A m^{-1}

The HI-3003 broadband exposure meter manufactured by Holaday Industries has been used to measure both electric and magnetic field strength. The meter is bulky and heavy and it was not found to be easy to use when performing measurements at height. Nevertheless, it has been valuable at sites where exposures in excess of environmental levels occur in the near field at ground level, for example at HF and MF transmitter stations. The newer Holaday HI-4417 Portable RF Survey System, shown in Figure 1, measures only electric field strength but it is lightweight and compact and the probe can be attached to the harness of an individual while climbing. The probe shields, shaped like truncated cones, are delicate, but the HI-4417 has been found to be easy to use when measuring electric fields at height.

FIGURE 1 Holaday HI-4417 Portable RF Survey System

The 8716 analogue power density meter manufactured by Narda Safety Test Solutions has been superseded by the 8718 digital survey meter, however both were used in the study. The meters are bulky and fairly heavy but have been useful in rooftop environments and for measurements at ground level. The Narda 8712 digital survey meter is more portable than the other Narda meters and has been used at height. There is the option of connecting Narda probes directly into the meter or using a flexible cable between the meter and probe and it has been found easier to use the flexible cable when carrying the instrument whilst climbing. However, if the instrument can be carried in an equipment bag, an advantage with connecting the probe directly into the meter is that single-handed operation becomes possible. The meter is shown with two probes in Figure 2.

FIGURE 2 Narda 8712 survey meter with two probes

Single-axis devices with small sensors have been used at a few sites to measure electric and magnetic field strengths in the vicinity of large field-perturbing structures. These measurement devices have included an EFS-1 electric field meter, attached to an insulating rod to reduce coupling with the body of the operator, and a 6 cm search coil connected to a digital storage oscilloscope. Measurements can be made over three mutually orthogonal axes using these instruments to provide the vector-summed resultant field strength.

2.2 Narrowband instrumentation

Some limitations of broadband instrumentation are its relative insensitivity, slow response time, and the lack of information on the frequencies of measured fields. These limitations can be overcome by making narrowband measurements employing a broadband antenna in conjunction with a receiver or a spectrum analyser. Receivers are essentially narrowband tuneable voltmeters that provide the frequency and amplitude of the signals to which they are tuned. Spectrum analysers are tuneable over a wider frequency range than receivers and they can be used to display the variation of amplitude over a specified portion of the spectrum. Spectrum analysers are usually scanned over a selectable frequency range and the displayed frequency and amplitude information can be stored for subsequent analysis. The most commonly used type of spectrum analyser is the superheterodyne analyser, which effectively sweeps the desired spectrum through a fixed-width bandpass filter.

Many antennas used in conjunction with spectrum analysers for narrowband measurements are not isotropic. Therefore, two or three measurements are required to determine the vector-summed resultant field strength if the direction of propagation and/or the frequency are unknown. Some antennas are also directional and this adds to the complexity of the measurements. The antennas also tend to be large, since they contain resonant elements, and this can give rise to perturbation in the near field and prohibit making a series of measurements with high spatial resolution. Moreover, the antennas may couple with nearby dielectric objects, potentially including the body of the operator of the instrumentation.

Narrowband equipment is expensive and difficult to use and the measurements are time-consuming. The equipment also tends to be very bulky, although lightweight portable spectrum analysers are now available. In addition some processing of the data is normally required to take account of the calibration of the receiving antenna and the loss in the connecting cable when converting the measured amplitude to field strength or power density. Consequently, narrowband equipment is predominantly the tool of specialists and is impractical for use in confined spaces and other environments where access is difficult.

2.2.1 Narrowband equipment employed in the study

Narrowband measurements have been carried out at a small number of sites where the exposure was generally below the threshold of detection of broadband equipment or where careful analysis of pulsed signals was required. The narrowband equipment consisted of a spectrum analyser connected to one of a choice of antennas via a coaxial cable. The threshold of detection for electric field strength using this equipment depended on the spectrum analyser settings but was typically of the order of 1 mV m^{-1}. Three broadband antennas were employed in conjunction with the spectrum analyser for measuring electric field strength over adjacent frequency ranges to cover the band 30 MHz to 18 GHz. The antennas were mounted on lightweight tripods providing stable support but permitting their orientation to be varied manually to achieve maximum coupling with fields emanating from different directions and with different polarisations.

The antennas used during site visits are listed in Table 3, together with the range of frequencies specified for each model. An Agilent E4407B spectrum analyser was used to display the frequency and received power of each detected radio signal. The power could be converted to electric field strength taking into account the antenna calibrations and losses in the connecting cable. The ridged guide horn antenna is shown with the spectrum analyser and a computer, used for capturing the data from the spectrum analyser, in Figure 3.

TABLE 3 Antennas used with a spectrum analyser for narrowband measurements

Manufacturer	Model	Type	Frequency range
Schaffner-Chase	VBA6106A	Biconical	30–300 MHz
Schaffner-Chase	UPA6108	Log-periodic	300–1000 MHz
EMCO	3115	Ridged guide	1–18 GHz

FIGURE 3 Narrowband measurement equipment consisting of a spectrum analyser connected to a ridged guide horn antenna mounted on a tripod. A computer is used to capture, and subsequently process, the data

2.3 Body current meters

The measurement of induced current is of interest since the quantity is internal to the body and, in certain circumstances, it is considered a more reliable indicator of exposure than electric field strength (Jokela and Puranen, 1999). Instrumentation has been developed that is sensitive to frequencies in the VHF band and below.

There are two main types of meter for measuring current induced in the body. Transformer clamps measure the currents flowing through the limbs, whilst foot current meters measure the current flowing through the feet to the ground. Meters are also available for measuring contact current, but this subject lies outside the scope of the study.

2.3.1 Foot current meters

Measurement of current flowing between the feet and the ground is achieved using two parallel conducting plates, separated by a slab of dielectric material and short circuited via a small resistance. The individual stands on the upper plate and the lower plate is placed on the ground. The induced current is calculated by Ohm's law from the potential difference measured across the resistor using a voltmeter incorporating, eg a diode detector. Alternatively the resistor and detector could be replaced by a thermocouple RF milliammeter connected in series with the two plates.

During the study, measurements were made using a HI-3701 induced current meter, manufactured by Holaday Industries and shown in Figure 4. The appearance of the device is similar to that of a set of bathroom scales and current is measured by placing the meter on the ground and standing upon it. The size and weight of the meter make it impractical for routine use when working at height. The usefulness of the meter in the study was limited by its frequency range which spanned 3 kHz to 100 MHz. The dynamic range of the meter was specified at 1–1000 mA.

FIGURE 4 Holaday HI-3701 induced current meter

2.3.2 Transformer clamps

Transformer clamps have the advantage over foot current meters in that they can be used in a greater range of environments. The clamp consists of a coil wound around a ferrite core and is generally placed around the wrist, ankle or neck. The current induced in the coil provides a direct measurement of current flowing through the region of interest in the body.

During the study, limb current was measured using an F-75 current transformer, manufactured by Fischer Custom Communications Inc, connected to a PCM4 current meter developed in-house (Blackwell, 1990). The instrument is sensitive to frequencies down to 100 kHz and its dynamic range is from 3 mA to 1 A. Three variants of the PCM4 have been developed in order to provide selectivity in upper cut-off frequencies. The respective cut-off frequencies for the three units are 70 MHz, 110 MHz and 250 MHz. This allows currents due to VHF broadcast transmitters in the 88–108 MHz band to be separated from those due to wide-area pagers in the 138 MHz and 153 MHz bands and to other transmitters operating at lower frequencies.

The F-75 current transformer is relatively light and can be comfortably clamped around the wrist. However, since there is no data logging facility, the instrument is more useful for spot measurements than for wearing for extended periods whilst carrying out other duties. The transformer can be clamped around the ankle of a slim adult, as shown in Figure 5, provided the footwear being worn does not cover the ankle. The PCM4 can be used for making spot measurements of ankle current at height but is unsuitable for wearing for extended periods since most riggers wear boots and since the design of the equipment makes it unwieldy and susceptible to damage in this type of environment.

FIGURE 5 Limb current meter consisting of a current transformer, clamped around the ankle, connected to a PCM4

A commercially available limb current meter has been developed by Holaday Industries and a model owned by one of the sponsors was used at some sites visited during the study. The HI-3702 responds to frequencies in the range 9 kHz to 110 MHz and has a dynamic range of 2–1000 mA. The transformer clamp has an internal diameter that is large enough to allow the device to be placed around the ankle, even when ankle-supporting footwear is being worn. The clamp is connected to a digital display unit via a fibre-optic cable. The display unit used in conjunction with the current clamp during the site visits had a data-logging function, however there was no facility for the automatic storage of measurements in the memory. The keypad on the unit had to be used each time the wearer wanted to record a reading. Although the HI-3702 was useful for making spot measurements at specific locations of interest, the instrument was impractical for wearing for long periods in many typical environments of RF exposure. This was because the transformer clamp was heavy, and the separate display device and interconnecting cable were considered an additional hindrance.

2.4 Standard RF measurement techniques

The performance of RF measurements during the study generally followed standard techniques described by a number of organisations in publications that contain practical guidance for assessing exposure. A standard on recommended practice for the measurement of potentially hazardous RF fields has been published by IEEE (1991). The standard also describes some of the different types of instrumentation available and their desirable characteristics. The publication covers the assessment of specific energy absorption rate (SAR) in tissue-equivalent materials, in addition to the measurement of external fields and body currents.

Guidance and suggestions for evaluating compliance with exposure guidelines have been given by the US Federal Communications Commission (FCC) in OET Bulletin 65 (FCC, 1997a). The Bulletin provides advice in predicting and measuring field strengths and in controlling exposures through administrative and other means. A supplement to the Bulletin has been published providing additional detailed information relevant to radio and television broadcast stations (FCC, 1997b).

The US National Council on Radiation Protection and Measurements (NCRP) has published a report containing a practical guide to the determination of exposure to RF fields (NCRP, 1993). The report describes instrumentation for measuring external field strength and outlines procedures for evaluating exposure. It also describes methods for performing practical measurements and computations of exposure specific to a number of different types of RF source.

In addition to the reports mentioned above, there are a number of monographs and technical notes produced by instrumentation manufacturers and others that provide advice on making measurements and using commercial products (Bitzer and Keller, 1999; Kitchen, 2001; IMC, 2004).

3 EXPOSURE MEASUREMENTS

Sites used for the purposes of broadcast, telecommunications and air traffic control have been visited in order to make spot measurements of electric and magnetic field strength and induced current. The measurements were conducted to provide an indication of the ranges of exposure typically encountered by workers at a variety of sites, and to evaluate the suitability of existing instrumentation for carrying out measurements in different environments, particularly at height. The frequencies transmitted at the various sites covered a broad spectrum from kilohertz frequencies to tens of gigahertz. A direct comparison of field strengths measured at different sites is inappropriate since the magnitude and distribution of dosimetric quantities, such as SAR, in body tissues vary with frequency for a given distribution and strength of the incident electric and magnetic fields.

3.1 VHF/UHF broadcast sites

Measurements of electric field strength were made at seven sites used for broadcasting FM radio and television signals. Magnetic field strength and limb current were also measured at some of these sites. Descriptions of the sites and the primary radio systems installed at them are given in Table 4 in which each site is identified by a unique number. The broadcast sites each hosted transmitters for one or more of the following.

a Analogue television
b Digital television
c National FM radio
d Local FM radio
e Digital audio broadcasting (DAB)

In addition to the radio systems listed, each site hosted a number of telecommunications systems such as base stations for mobile phone and wide-area paging networks and point-to-point microwave links. The antennas at most of the sites were mounted on self-supporting lattice towers or guyed masts. These had ladders running up inside them and maintenance platforms were situated at regular intervals. Site 5 was a concrete tower, and access to its upper levels was normally gained by use of an elevator installed within the structure.

At sites where high-power analogue UHF television transmitters were installed, the signals were generally transmitted via arrays of antennas enclosed within cylindrical weatherproof radomes at the top of the mast or tower. In these cases, a platform was usually installed a few metres below the cylinder to facilitate maintenance. The exception was at Site 4 where the antennas for one television channel were mounted 80 m above ground level. It was possible to climb through the arrays at this site and also to climb past some of the television antennas at Site 5 without reducing the transmitted power. However, it was not possible to climb through the arrays of analogue television antennas at the other sites. Digital television signals were generally transmitted at lower powers than the analogue signals at sites where transmitters for both systems had been installed. The antenna arrays for digital television were normally mounted below the analogue arrays on the mast or tower and could be climbed past without the need to reduce power.

National FM radio signals were generally transmitted via arrays of dipole antennas mounted around the upper section of the mast or tower. The VHF arrays were typically arranged in three or four columns, separated by an azimuthal angle of 120° or 90° respectively. Maintenance platforms were generally installed above and below the arrays, and at some sites there were also platforms within the arrays. At Sites 2, 4 and 7, individuals were allowed to climb through the arrays only under conditions of reduced transmitter power.

TABLE 4 VHF/UHF broadcast sites at which portable survey instrumentation was used

Site	Height of structure (m)	System	Number of channels	Effective radiated power per channel (kW)	Measurements
1	60	National radio	4	10	Electric field Magnetic field
		Local radio	2	2.2[1]	
		DAB	–	2	
2	225	Analogue television	4	1000	Electric field
		National radio	5	250[1,2]	
		DAB	–	10	
3	104	National radio	4	1	Electric field Magnetic field
		Local radio	2	1[1]	
4	152	Analogue television	5	100	Electric field Wrist current
		Digital television	6	2	
		National radio	5	10[1,2]	
		Local radio	2	2[1]	
5	331	Analogue television	5	870	Electric field
		Digital television	6	5[3]	
		DAB	–	10	
6	110	Local radio	3	4[4]	Electric field Magnetic field
7	224	Analogue television	4	500	Electric field Ankle current
		Digital television	6	5[5]	
		National radio	5	250[2]	
		Local radio	1	250[2]	
		DAB	–	9[2]	

[1] Effective radiated power of one of the channels unknown

[2] Power reduced during measurements

[3] One channel operating with an effective radiated power of 2 kW

[4] Effective radiated power of two of the channels unknown

[5] One channel operating with an effective radiated power of 10 kW

A variety of antennas was used in association with the transmitters for regional VHF FM radio at the sites visited. Often the antennas were mounted on a single side of the structure and the height between the uppermost and lowermost elements was generally much less than that for an array used for national broadcasts. The power output of local radio transmitters was often less than that for national transmitters. Consequently, it was not always necessary to reduce the power to permit access to regions of the structure above the antennas.

The measurements of electric field strength made around the UHF television antennas are summarised in Table 5. Measurements of electric and magnetic field strength and limb current made in the vicinity of broadcast VHF antennas are summarised in Tables 6 and 7. Ambient field strengths were generally measured at least 0.5 m away from conducting structures. A range of results is given where the field strength was found to exhibit spatial variation within the region of the location specified. Limb currents are reported in ranges and these reflect the different currents drawn when different postures were adopted and when different parts of the tower structure were grasped. Localised regions of elevated field strength were sometimes found close to feeders, splitters and steelwork and, in these cases, the spatial maximum values 0.1–0.2 m away from the specified items are recorded.

TABLE 5 Electric field strength measured in the vicinity of UHF television antennas

General location	Details	Electric field strength ($V m^{-1}$)		
		Site 2	Site 4	Site 5
In between two antenna arrays	Ambient level	–	–	60–100
Top platform, just beneath main analogue array (four channels)	Ambient level	40–90	10–20	–
	Near steelwork	–	25	–
	Near splitter	>270	–	–
Inside secondary analogue array (single channel)	Ambient level	–	40	–
	Near ladder	–	60	–
	Near feeders	–	90	–
Inside digital array	Ambient level[1]	–	20–30	–

[1] No localised field strengths materially exceeding the ambient level were found in this region

A wide range of electric field strengths are reported in Tables 5 and 6 and this reflects the diversity of exposure conditions at different sites and the range of exposures present over different regions of the tower at any single site. Factors that influenced ambient exposure levels included transmitted power, antenna design and positioning, screening, the distance of closest approach to an antenna and the angles of azimuth and elevation with respect to the antenna or array. It was observed that the maximum ambient levels around maintenance platforms were usually no greater than 100 $V m^{-1}$. Field strengths exceeding 100 $V m^{-1}$ were measured close to steelwork, feeders, splitters and directly behind VHF antennas. These electric fields were generally highly localised in the near-field conditions that prevailed in this type of environment and, therefore, would not have been representative of whole-body exposure.

A general trend for the ambient electric field strength to decrease with decreasing height was observed on the lower levels of the towers in regions beneath all the broadcast antennas. However, localised regions of field strength above ambient levels were sometimes discovered close to telecommunications antennas mounted on the structures. Measurements close to telecommunications antennas are discussed in the following section.

The magnetic field strengths given in Table 7 covered a smaller range than the electric field strengths discussed above. This was partly due to the relative insensitivity of magnetic field probes, when compared with electric field probes under plane-wave conditions. The near-field exposure conditions may have been another contributing factor. The use of magnetic field probes was more limited than that of electric field probes since the frequency ranges specified for the magnetic field probes that were available to the study did not extend into the UHF band. The greatest magnetic field strengths detected at the sites visited were generally in the region of 0.2–0.4 A m^{-1}.

TABLE 6 Electric field strength measured in the vicinity of VHF broadcast radio antennas

		Electric field strength (V m^{-1})					
General location	Details	Site 1	Site 2	Site 3	Site 4	Site 6	Site 7
Platform above main array (four channels)	Ambient level	50–100	100	–	–	–	–
	Near splitter	–	190	–	–	–	–
Platform beneath main array	Ambient level	30	60	–	20	–	–
	Near ladder	–	–	–	40–80	–	–
	Near feeders	–	–	–	200	–	–
	Near steelwork	–	–	–	300	–	–
Inside main array	Ambient level	120	150–250	–	–	–	20–25
	Near ladder	270	–	–	–	–	–
	Near steelwork	390	–	–	–	–	30
	Close behind antennas	240	480	–	–	–	–
	Near splitter	450	–	–	–	–	–
	0.5 m outside structure	–	–	–	–	–	40–50
Adjacent to local FM radio antennas (single channel)	Ambient level	–	–	20–30	15–25	–	–
	Edge of structure	–	–	50	–	–	–
	1 m outside structure	–	–	95	–	–	–
	Near feeders	–	–	–	150	–	–
Platform between local FM radio antennas	Ambient level	–	–	–	–	30–40	–
	Near steelwork	–	–	–	–	100	–
	Near splitters	–	–	–	–	200	–
Platform on outside of structure beneath local FM radio antennas	Ambient level	–	–	–	–	10–50	–
	Near steelwork	–	–	–	–	80	–

TABLE 7 Magnetic field strength and limb current measured in the vicinity of VHF broadcast radio antennas

		Magnetic field strength ($A\ m^{-1}$)			Limb current (mA)	
General location	Details	Site 1	Site 3	Site 6	Site 4	Site 7
Platform below main array	Ambient level	–	–	–	20–55[1]	3–6[2]
Inside main array	Ambient level	0.3	–	–	30–80[1]	15–50[2]
	Near steelwork	0.4	–	–	–	–
Adjacent to local FM radio antennas (single channel)	Ambient level	–	–	–	15–30[1]	–
	Edge of structure	–	0.2	–	–	–
	1 m outside structure	–	0.4	–	–	–
Platform on outside of structure below local FM radio antennas	Ambient level	–	–	<0.05–0.16	–	–
	Near steelwork	–	–	0.23	–	–

[1] Current flowing through the wrist

[2] Current flowing through the ankle

Use of the limb current meter at Sites 4 and 7 showed that a range of wrist and ankle currents could be measured at any given location depending on the orientation and posture of the individual and whether contact was being made with any part of the structure by the hand and, if so, the particular item being grasped.

3.2 Telecommunications masts and rooftops

Measurements of electric and magnetic field strength have been made at seven sites used for telecommunications purposes. Radio systems located at these sites included base transceiver stations (BTSs) for mobile telephony and wide-area paging, private mobile radio (PMR), microwave point-to-point links and other miscellaneous VHF and UHF transmitters. The mobile phone base stations operated according to the second-generation digital Global System for Mobile Communications (GSM) standard; base stations for Terrestrial Trunked Radio (TETRA) networks were being installed at some of the sites, however these were not operational when the spot measurements were carried out. Descriptions of the sites and some of the radio systems installed at them are given in Table 8. Base stations are listed separately under sites at which more than one system had been installed. Sites 6 and 9 hosted broadcast VHF transmitters in addition to the telecommunications systems noted (measurements at Site 6 were also reported in Section 3.1).

The three lattice towers identified in Table 8 had ladders running up inside them and maintenance platforms were situated at regular intervals. The concrete tower had a staircase and ladder inside the structure and doors in the side of the structure gave access to open-air platforms, around which the antennas were mounted. Many of the antennas at the sites could be approached sufficiently closely that physical contact could be made with them (or their radomes), albeit with the limbs alone. Table 8 indicates where the antennas were mounted above head height at rooftop sites such that they were not accessible under normal circumstances.

TABLE 8 Telecommunications sites at which portable survey instrumentation was used

Site	Description	System	Antennas	Positions of antennas	Measurements
6	Lattice tower	GSM BTS	Sector antennas	Mounted on tower	Electric field
		GSM BTS	Sector antennas	Mounted on tower	
		GSM BTS	Sector antennas	Mounted on tower	
8	Rooftop	Pager BTS	Colinear	Edge of rooftop	Electric field Magnetic field
		GSM BTS	Sector antennas	Edge of rooftop	
		GSM BTS	Sector antennas	Top of stub tower[1]	
		Microwave links	Dish antennas	On wall[1]	
9	Lattice tower	Pager BTS	Dipoles[2]	Mounted on tower	Electric field
		Pager BTS	Folded dipoles[2]	Mounted on tower	
		GSM BTS	Sector antennas	Mounted on tower	
10	Rooftop	Pager BTS	Colinear	Edge of rooftop	Electric field Magnetic field
		Pager BTS	Folded dipoles[2]	Edge of rooftop	
		Microwave links	Dish antennas	Edge of rooftop	
11	Lattice tower	Microwave links	Dish antennas	Mounted on tower	Electric field
12	Concrete tower	GSM BTS	Sector antennas	Mounted on tower[1]	Electric field
		GSM BTS	Sector antennas	Edge of platform	
		GSM BTS	Sector antennas	Edge of platform	
		Microwave links	Dish antennas	Edge of platform	
13	Rooftop	Pager BTS	Colinear	Edge of rooftop[1]	Electric field Magnetic field
		GSM BTS	Sector antennas	Top of stub tower[1]	
		GSM BTS	Sector antennas	Corner of rooftop	

[1] Antennas mounted above head height

[2] Stacked pair of antennas

The pager base stations encountered at the telecommunications sites employed omnidirectional antennas that were either colinear in design or consisted of a pair of resonant dipoles, or folded dipoles, stacked one above the other. The pager antennas on lattice towers were generally mounted at the end of a boom such that the antennas were typically two or more metres away from the main structure. At rooftop sites, where colinear antennas were used, it was sometimes possible to make physical contact with the antenna shroud or, if the antenna was mounted above head height, with its supporting pole.

The GSM base stations at all the sites visited employed between three and twelve sector antennas each. Where the antennas were mounted on a stub tower, the distance of closest approach was usually at least 1 m, even if it was possible to stand directly beneath them. It was often possible to get within a few tens of centimetres of antennas mounted around the edges of rooftops and to touch the antennas with the hands. Electric field strength could be measured directly in front of the antennas in some situations, although it was generally not possible to expose the head or torso in these regions. Where the antennas were mounted on lattice towers, it was often possible to climb to within a few tens of centimetres behind the antennas but access to the front faces of the antennas was more difficult.

Measurements of electric field strength were made directly behind microwave dish antennas and their feeders at a number of sites. Access to the front faces of the antennas was normally difficult and few measurements were made in these regions. The probe used to measure electric field strength in the vicinity of microwave dish antennas had a detection threshold of 6 V m^{-1} and in the majority of instances this field strength was not exceeded.

The measurements of electric field strength made around telecommunications antennas are summarised in Table 9. Measurements of magnetic field strength were performed at the rooftop sites and are summarised in Table 10. Ambient field strengths were generally measured at least 0.5 m away from conducting and dielectric structures. A range of results is given where the field strength was found to exhibit spatial variation within the region of interest. Field strengths reported close to antennas are generally spatial maximum values measured 0.1–0.2 m away from the antenna specified. Observations of electric and magnetic field strength often varied over time, indicating that many systems transmitted intermittently, possibly using variable numbers of carriers. All the reported field strengths are temporal maxima and would, therefore, provide overestimates of time-averaged exposures.

TABLE 9 Electric field strength measured in the vicinity of telecommunications antennas

	Electric field strength (V m^{-1})						
Location	Site 6	Site 8	Site 9	Site 10	Site 11	Site 12	Site 13
Ambient level above platforms/rooftop	3–5	1–20	8–50	10–40	≤17	4–12	<1–7
Near pager antenna	–	–	–	350	–	–	–
1–2 m laterally from pager antennas	–	–	50–75	–	–	–	–
Near horizontal boom for pager antenna	–	–	–	570	–	–	–
Near vertical support pole for pager antenna	–	–	–	60–90	–	–	50–90
1 m from vertical support pole for pager antenna	–	–	–	–	–	–	15–19
Beneath GSM sector antennas	–	20	–	–	–	≤11	–
Behind GSM sector antennas	≤8	24	–	–	–	≤11	≤12
Adjacent to GSM sector antennas	–	–	–	–	–	23	–
In front of GSM sector antennas	–	30	–	–	–	72	–
Behind microwave dish antennas	–	–	–	–	≤11	≤9	–
In front of microwave dish antennas	–	<6	–	75[1]	–	–	–
Near unidentified VHF/UHF antennas	–	–	–	270	–	13	–
Near protective barrier around perimeter of roof	–	–	–	180	–	–	–

[1] The electric field strength measured at this location was likely to have been largely due to other nearby VHF/UHF antennas, rather than the 1.2 m microwave dish

TABLE 10 Magnetic field strength measured in the vicinity of telecommunications antennas at three rooftop sites

Location	Magnetic field strength (A m^{-1})		
	Site 8	Site 10	Site 13
General ambient level over roof area	≤0.11	≤0.16	≤0.04
Near pager antenna	0.16	0.57	–
Near horizontal boom for pager antenna	–	0.88	–
0.15 m from vertical support pole for pager antenna	–	–	0.1–0.2
1 m from vertical support pole for pager antenna	–	–	0.05–0.06
Near unidentified VHF/UHF antennas	–	0.62	–
Near protective barrier around perimeter of roof	–	0.25	–

A wide range of ambient electric field strengths are reported in Table 9 for the sites that were visited. The strongest fields were found near antennas associated with pager base stations; field strengths of up to several tens of volts per metre were measured at certain sites and these measurements were representative of whole-body exposure at easily accessible locations. Electric field strengths of several hundred volts per metre were measured close to pager antennas and nearby conducting structures, however these fields were confined to more localised regions. Pager base stations typically transmit powers up to several hundred watts, whereas GSM base stations generally do not feed antennas with powers greater than a few tens of watts. Field strengths around sector antennas for GSM base stations were typically no greater than 25 V m^{-1}, except directly in front of transmitting antennas where the fields were stronger. The electric field strengths in front of and behind dish antennas could usually not be measured above the detection thresholds of the instrumentation. An exceptional case was found at Site 10 where a field strength of 75 V m^{-1} was measured in front of a 1.2 m dish antenna. This particular antenna was facing towards other VHF and UHF antennas and it is likely that the field strength was largely due to these rather than the microwave dish.

The ambient magnetic field strengths at rooftop sites given in Table 10 were generally in the region of, or only slightly above, the detection thresholds of the probes used to carry out the measurements. It was possible to measure greater field strengths close to pager antennas and to other VHF/UHF antennas used for unknown purposes. Magnetic field strengths could not be measured in the vicinity of GSM sector antennas since no instruments were available that covered the necessary frequency range.

3.3 AM transmitter stations

Electric and magnetic field strengths and induced currents have been measured at an HF station, an MF station and a VLF/LF station. Measurements were made outdoors, in the areas around the antennas, and inside the main building at each site. Details of the three sites and the results from the measurements are given below. The field strengths encountered at many of the locations visited at the HF and MF stations exhibited considerable variation over time due to voice modulation of the carrier frequency. In these situations the reported results are the maximum values recorded during the period of measurement.

3.3.1 HF station

The HF station employed six 250 kW transmitters and four 300 kW transmitters and all the RF supply units, known as senders, were located in the transmission hall inside the main building. The six 250 kW senders comprised separate transmitter and modulator units and a preamplifier; the more modern 300 kW senders consisted of two units with a narrow aisle between them. Electric and magnetic field strengths were measured around the senders that happened to be transmitting during the visit, and wrist currents arising from contact between the hand and the senders were also measured. The strongest field strengths were measured adjacent to windows in the transmitter and modulator units.

The HF signals generated by the senders were fed to switchstations that were used to route each signal to the appropriate antenna. One of the switchstations was fully screened to allow personnel access to the area. The antennas were fed by overhead open-wire feeders from the switchstations. Each antenna array had a set of switches associated with it in order to select the elements for excitation and to control the direction and elevation of transmission. Measurements of electric and magnetic field strength and induced current were made in the switchstation, beneath the feeders and in the vicinity of the switches located by some of the antennas. The measurements obtained during the site visit are summarised in Tables 11 and 12. Ranges of results are given in some cases where the field strengths were found to vary over the region specified. Where no range is given, the value may be considered the spatial maximum. Ranges of induced currents are given where these were found to depend on location or the posture of the body.

TABLE 11 Electric and magnetic field strengths measured at the HF transmitter station

General location	Details	Electric field strength (V m^{-1})	Magnetic field strength (A m^{-1})
Transmission hall	Ambient level	1.5–2.5	–
250 kW senders	Adjacent to window	300	1.0
	5 cm from window	100	–
	10 cm from window	–	0.3
	30 cm from window	–	0.1
	50 cm from window	10	–
300 kW senders	Gap between doors	–	1.4–1.7
	Aisle between units	–	0.9
Switchstation	Boundary of area	–	0.7–1.0
	Adjacent to switch casings	300	≤0.1
Antenna field	Beneath primary feeders	100	0.7
	Beneath switching unit	100	1.4–1.7
	Beneath secondary feeders	150	0.3–0.4

TABLE 12 Induced currents measured at the HF transmitter station

Exposure conditions	Current (mA)	
	Wrist	Ankle
Contact of hand with transmission unit of 250 kW sender	3	–
Contact of hand with casing of 300 kW sender	50	–
Standing in switchstation	–	50
Contact of hand with switch casing in switchstation	110	150
Standing beneath primary feeders	–	130–240[1]
Standing beneath switching unit	–	130–180
Finger contact with structure supporting switching unit	100	–
Grasping contact with structure supporting switching unit	400–900	120
Standing beneath secondary feeders	–	120

[1] Up to 270 mA upon removal of shoes

3.3.2 MF station

The MF station visited during the study transmitted on two frequencies: 648 kHz and 1296 kHz. Four transmitters were located at the station, however no more than two were operational at any given time. Electric and magnetic field strengths were measured around a 600 kW transmitter that employed dynamic amplitude modulation, which is a power-saving system whereby the carrier amplitude is decreased when the modulation depth is low. Field strengths were also measured around an isolation switch that directed the signal output from the transmitter to the appropriate antenna via air-cored coaxial feeders. The strongest field strengths were measured adjacent to windows in the casings of the transmitter and switch units. Currents induced when contact was made with the casings were additionally measured.

The 1296 kHz signal transmitted from the station was fed to a double Yagi array consisting of two rows of three vertical monopole antennas, both rows pointing in the direction of transmission. The central pair of elements were live and received the signal for transmission via underground feeders. The front and rear pairs of elements were passive and formed a director and reflector respectively. The active elements were surrounded by a protective fence; the passive elements were unfenced. The 648 kHz signal was fed to a five-element end-fire array approximately 200 m long. The five vertical monopoles were arranged in a straight line, pointing in the direction of transmission. The primary emitter was the central element, although the remaining four elements were also live, fed by branches carrying a fraction of the signal strength from the main feeder. The elements were fenced and a cabin housing the matching inductor and other electrical equipment was situated at the foot of the central mast. A single monopole antenna was also situated at the site that served as a back-up antenna for the 648 kHz array. An earth mat was buried underground beneath the area around the antennas. The mat was exposed above the surface in some regions, particularly around the antenna structures where the ground was stony.

Measurements of electric and magnetic field strength were made around the central element of the 648 kHz antenna and the monopole whilst the 1296 kHz antenna and monopole were inactive. Measurements were also made around the 1296 kHz antenna whilst transmissions were being broadcast on both frequencies. Induced currents were additionally measured. The monopole was earthed to allow access to the area inside the enclosure surrounding the antenna. The measurements obtained during the site visit are summarised in Tables 13 and 14. Ranges of results are given in some cases where the field strengths were found to vary over the region specified, as above. Where no range is given, the value may be considered the spatial maximum.

TABLE 13 Electric and magnetic field strengths measured at the MF transmitter station

General location	Details	Electric field strength (V m^{-1})	Magnetic field strength (A m^{-1})
Transmitter	5 cm from window	160	79
	10 cm from window	–	1.3
	30 cm from window	<10	<0.4
Isolation switch	5 cm from window	30–50	1.6
	15 cm from window	–	0.07
Central element of 648 kHz antenna[1]	Near protective fence	460–610	0.5–1.7
	Inside cabin	<22	1.6
Active element of 1296 kHz antenna[2]	Near fence, 1–2 m above ground	430–700	0.37–1.7
	Near fence, close to ground	230	10
Director of 1296 kHz antenna[2]	Near leg of mast	660	10
	50 cm from mast	–	8.4
Monopole antenna[1]	Ambient level inside enclosure	≤22	0.20–0.26
	Close to ground above underground feeder	–	0.8

[1] Transmissions only at 648 kHz

[2] Transmissions at both 648 kHz and 1296 kHz

TABLE 14 Induced currents measured at the MF transmitter station

Exposure conditions	Current (mA)		
	Wrist	Ankle	Neck
Contact of hand with transmitter	≤6	–	–
Contact of hand with isolation switch	≤1	–	–
Standing close to fence surrounding the central element of the 648 kHz antenna	–	–	18
Contact with handrail of stairway to matching inductor cabin	40	–	–
Standing close to fence surrounding one of the active elements of the 1296 kHz antenna	9	17	29
Contact of hand with one of the directors of the 1296 kHz antenna	130–150	40	–
Standing close to one of the directors of the 1296 kHz antenna (no physical contact)	5–10	10	12
Standing close to fence surrounding monopole	<1	–	–
Contact of hand with outer guy wires of monopole	<1	–	–
Contact of hand with monopole	17–25	–	–

3.3.3 VLF/LF station

The VLF/LF station transmitted on two frequencies during the site visit, one in the VLF band and the other at 60 kHz, in the LF band. A second low frequency signal that may be transmitted simultaneously with the other signals from the station was not being produced on the day of the visit. The antennas for the three transmitters were supported by twelve 250 m masts which were earthed, as were their stays. The VLF antenna was configured in a 'top hat' arrangement and was fed by an up-lead which met the main triatic, suspended between two of the masts, midway along the catenary. The LF antennas were 'T' shaped, each comprising a single catenary suspended between two of the masts at a height of 180 m. The two antennas were suspended from different pairs of masts and each was fed by an up-lead rising vertically from a tuning coil beneath the centre of the antenna. An earth mat was buried underground beneath the entire site.

Measurements of electric and magnetic field strength were made at various locations around the site and the results are summarised in Table 15. The strongest fields were found inside the room housing the VLF tuning coil. Induced currents were also measured and were found to be no greater than 2 mA in areas outside the main building.

TABLE 15 Electric and magnetic field strengths measured at the VLF/LF transmitter station

Location	Electric field strength (V m^{-1})	Magnetic field strength (A m^{-1})
Outside main building	200–400	0.3–1.4
On driveways approaching main building	30–300	0.2–0.9
Adjacent to building housing LF tuning coil	500	2.1
Inside room housing VLF tuning coil (generally accessible areas)	200–1000	13–41
Inside room housing VLF tuning coil (controlled areas)	3000–3600	68–92
Beneath antenna array	60–650	0.3–1.0

3.3.4 Summary

Electric field strengths exceeding 100 V m^{-1} were measured close to the transmitters at the HF and MF stations, however these fields were encountered only in highly localised regions close to viewing windows in the units. The field strengths were typically reduced by a factor of ten at distances of a few tens of centimetres away from the windows. Workers are unlikely to spend a substantial amount of time close to the windows of powered transmitters, therefore the strongest measured fields would not be expected to represent typical exposures.

Electric and magnetic field strengths were measured in the antenna field at all three AM stations and a wide range of values was obtained. Field strength was found to vary with height above the ground and with proximity to antenna elements, feeders and other structures. The strongest electric fields were typically in the region of several hundred volts per metre, however these may not be representative of the time-averaged exposures of workers whilst operating in the vicinity of the antennas.

Electric field strengths measured near the antennas at the MF and VLF/LF stations were greater than those measured in the field at the HF station, however this is not necessarily significant in terms of exposure since energy is absorbed less efficiently by the body at the lower frequencies.

3.4 Air traffic control

Three types of air traffic control site were visited during the course of the study, and these hosted radar, navigation and communications systems. Measurements of electric field strength were made at each site and the results are summarised below.

3.4.1 Radar

Measurements of electric field strength have been made at two radar sites and, in both cases, the measurements were made while the antenna was rotating. Narrowband measurements were made at the first site where the antenna was located at ground level and surrounded by a wooden fence. Measurements were made of the maximum root mean square (rms) field strength recorded when pulses were transmitted at the point in the antenna's rotation when the bore-sight directions of the radar antenna and receiving antenna were coincident. The measured field strengths were converted to mean values taking account of the duty factor and the rotation reduction factor of the radar antenna. Rotation reduction factors were derived from theoretical calculations of the azimuthal beamwidth for the measurement positions in the near field. The narrowband results are summarised in Table 16. A range of field strengths is reported where measurements were made at more than one position.

TABLE 16 Electric field strengths obtained from narrowband measurements at a radar site

Location	Electric field strength ($V m^{-1}$)	
	Maximum	Mean
Inside transmission room	91	1.1
Outdoors on site thoroughfare	240–560	2.3–3.6
Car park	32	0.10
Inside control room	1.9–4.2	0.006–0.013

Broadband measurements were made at the second radar site, and here the antenna was mounted above the buildings at the site on top of a concrete plinth. The roof of the plinth was used as a platform, known as the aerial platform, to which access could be gained via a trapdoor. The aerial platform was the closest accessible location to the rotating antenna. Measurements were made inside equipment rooms at the site and at outdoor locations, including the aerial platform, and the results are summarised in Table 17. The field strength above the aerial platform varied periodically with the rotation of the antenna and the range of results reported in Table 17 is representative of the range of field strengths recorded over time at most positions over the platform.

TABLE 17 Electric field strengths measured using broadband equipment at a radar site

Location	Probe type	Electric field strength ($V m^{-1}$)
Ambient levels in equipment rooms	Diode	<6
Close to travelling wave tube inside transmitter cabinet	Thermocouple	23
Aerial platform	Diode	19–51
Outdoors at ground level	Diode	≤6

The uncertainties in the results obtained with the diode probe are likely to be greater than the measurement uncertainty specified by the manufacturer of the instrument due to several factors. These include the non-plane wave conditions at most of the locations, perturbation of the incident fields by the body of the operator and other nearby structures and the characteristic behaviour of diode detectors when measuring pulsed signals. Information produced by the manufacturer of the instrument suggested that the displayed field strength could deviate from the true rms value by several decibels when using diode probes to measure the field strength produced by stationary radars (Keller, 1996; Narda, undated), however data for the specific model of probe used during the site visit were not available. The uncertainty of the measurements made at outdoor locations is likely to have been greater still since the measured fields would have been produced by the antenna which was rotating. The meter would be expected to display a reading below the rms field strength in the main beam if the integration time of the detector is long compared with the period during which the probe is illuminated by the beam in each rotation. The illumination time in the far field was in the region of 20 ms for the type of radar visited and this is less than the integration time of many diode detectors, although information specific to the probe used during the visit was not available.

Clearly there are difficulties in making accurate measurements of exposure at radar facilities using broadband equipment. Measurements using narrowband equipment are more time-consuming and often impractical. Nevertheless, the results from the two site visits indicated that at most of the locations routinely occupied by personnel, eg in the equipment rooms and outdoors, the mean electric field strengths were no more than a few volts per metre.

3.4.2 Navigation

Electric field strengths have been measured at two navigational aids sites. The first site hosted a Doppler VHF omnidirectional range (DVOR) and distance measuring equipment (DME). A non-directional beacon (NDB) operating in the MF band was situated at the second site. Electric field strengths at locations typically occupied by engineers when attending the DVOR/DME site were at or below 1 V m^{-1} both inside the site building and outdoors. Field strengths in the range 5–7 V m^{-1} were measured above the roof, however personnel would not usually require access to the roof while the transmitters are operating.

The NDB antenna design was based on a mast with delta cross section that was isolated from the earth. Three capacitive wires stretched from the top of the mast to the ground 13 m away from the foot of the mast and these were also isolated from the earth. The mast was located inside a fenced enclosure that covered a square area with 4 m sides. A cabinet housing an aerial tuning unit (ATU) was situated next to the mast inside the enclosure. An earth mat was buried underground to provide a ground plane. The transmitter equipment was housed in a brick building 14 m away from the antenna. The results of the measurements of electric field strength at the NDB site are summarised in Table 18.

TABLE 18 Electric field strengths measured at a non-directional beacon

Location	Electric field strength (V m^{-1})
Inside site building	≤1
Outside site building, 1 m from wall	1.3–12
Outside mast enclosure, 0.5 m from fence	70–120
Inside enclosure, 1 m from mast	250–>300
Inside enclosure, 20 cm from ATU cabinet	150–>300

3.4.3 Communications

Electric field strengths were measured at a communications site used for air traffic control and other purposes. Broadband measurements showed that the ambient field strength was below 1 V m^{-1} inside the site building and did not exceed 1 V m^{-1} at any location outdoors at the site, 1.5 m above ground level. The strongest fields were measured inside transmitter cabinets after the rear panels had been removed and the maximum recorded electric field strength was 5 V m^{-1}. Narrowband measurements at one outdoor location yielded a field strength of 0.6 V m^{-1}. An analysis of the signal frequencies established that the field strength was largely due to signals from transmitters not at the air traffic control communications site, but at other broadcast and telecommunications sites that could be observed nearby.

3.5 Satellite uplinks

A satellite earth station was visited during the study in order to assess the exposures of workers to electric fields. Magnetic field instrumentation sensitive to the frequencies transmitted from the site was not available. The maximum powers fed to the dish antennas were a few tens of watts. The power was distributed over large aperture areas and the dishes were directed with a positive elevation above ground level, therefore the electric field strengths over the height of a human body standing on the ground were found to be low. The electric field strength in front of most of the antennas 1.5–2.5 m above the ground was in the region of or below 6 V m^{-1}, the detection threshold of the instrument used during the visit. The maximum electric field strength recorded at the site was 30 V m^{-1} and this was obtained near the lower edge of the aperture of one of the smaller antennas that radiated a relatively high power.

3.6 Correlation between electric field strength and ankle current

Simultaneous and near-simultaneous measurements of current induced in the ankle and electric field strength (external to the body) were made at three of the sites visited during the study. These sites consisted of an MF station, an HF station and a broadcast site with a mast that supported antennas associated with high-power VHF and UHF systems. The relationship between limb current and SAR has previously been investigated through finite-difference time-domain (FDTD) calculations using a voxel model of the body (Dimbylow, 1997b; 2002). This work has allowed calculations of the current that would be induced in the ankle under conditions of plane wave irradiation of the whole body with an electric field strength of 1 V m^{-1}. The calculations were performed at frequencies between 1 MHz and 80 MHz for the body standing on a grounded surface, both barefoot and with shoes on, and isolated in air. The results are shown in Figure 6.

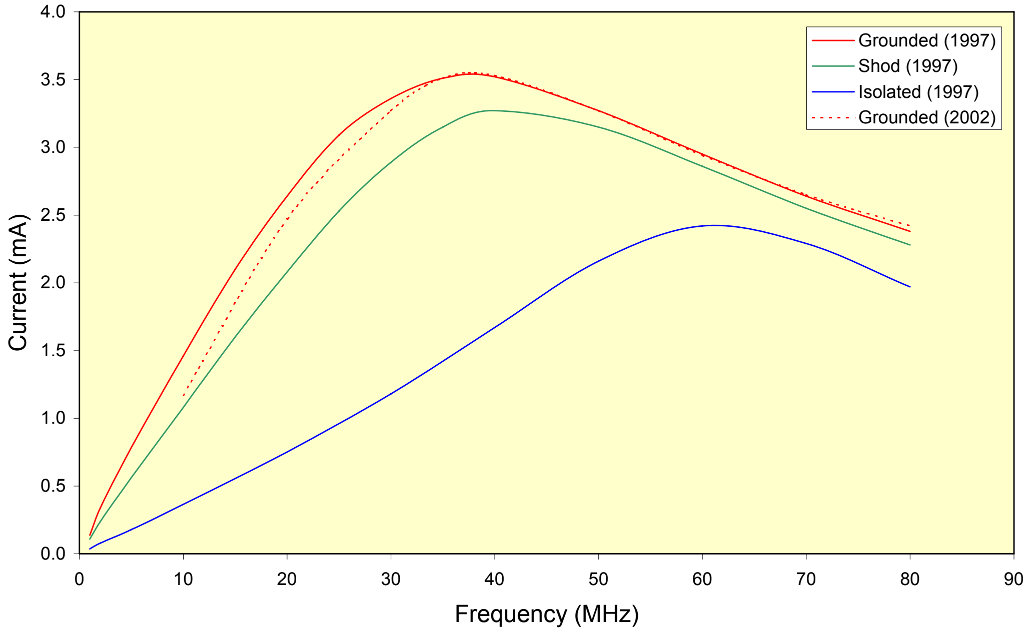

FIGURE 6 Ankle currents induced by a plane-wave external electric field strength of 1 V m^{-1}

The results of measurements of electric field strength and ankle current made at the same time or within a few minutes of each other at the three sites described above are given in Table 19. The majority of ankle current measurements were made with the subject free-standing and wearing shoes. However, when the subject was on the lattice structure of the VHF/UHF mast, he was also making contact with the structure with his hands. Most of the measurements of electric field strength were made using portable survey equipment, however some of the measurements on the mast were made using a body-worn personal exposure monitor. These latter measurements may have provided underestimates of the body-absent electric field strength due to shielding by the body. Ankle current was measured using the instrumentation described in Section 2.3.2. In many cases the electric field strength was found to exhibit considerable spatial variation and, additionally, it was often found to vary over time. These variations are reflected in the ranges of field strength reported in Table 19. Where a single value is given, this usually represents the spatial and temporal maximum, however the single values given for the measurements using the personal exposure meter were the values recorded at the instant that the ankle current was measured. Likewise, ankle current was typically found to vary over time and a dependence was observed on the position and posture of the subject and, at the third site, also on the points of contact with the mast structure. Again, ranges of values indicate this variability and single values represent maximum measured currents.

TABLE 19 Electric field strengths and ankle currents measured at MF and HF stations and at a VHF/UHF broadcast site. Also given is the ankle current that would be expected from the measured field strength based on numerical computations using a voxel model of the body with the assumption of plane-wave conditions

Site	Location	Dominant frequency (MHz)	Electric field strength (V m^{-1})	Ankle current (mA)	
				Measured	Expected
MF station	Near active antenna element	1.3	230–460	17	40–80
	Near passive antenna element	1.3	660	10	110
HF station	Switchstation	6–23	100–200	50	70–460
	Beneath primary feeders	6–23	100	130–240	70–230
	Beneath primary feeders[1]	6–23	100	270	90–280
	Beneath secondary feeders	11	30	120	36
	Beneath secondary feeders	9	150	150	150
	Beneath switching unit	9	100	30	100
VHF/UHF mast	On platform, near VHF antennas	90–100	20–30	15–50	40–60
	On platform, near VHF antennas	90–100	45[2]	23	90
	On lattice, near VHF antennas	90–100	66[2]	21	130
	On lattice, near VHF antennas	90–100	51[2]	28	100
	On lattice, near VHF antennas	90–100	61[2]	23	102

[1] Shoes removed

[2] Measured using a body-worn personal exposure monitor

The data shown in Figure 6 can be used to estimate the ankle currents that would be expected under conditions of plane-wave exposure to the electric field strengths given in Table 19. These expected values of ankle current are also shown in the table. A value of 2.0 mA per V m^{-1} was assumed for the VHF frequencies since an extrapolation of the computed data would be expected to yield a value close to this, both for a grounded body and for one wearing shoes. A coefficient of proportionality of 0.17 mA per V m^{-1} was assumed for the frequency 1.3 MHz, representing the conditions for a person wearing shoes. The coefficients assumed for the range of frequencies transmitted from the HF station were between 0.9 and 2.8 mA per V m^{-1} for a grounded body, and between 0.7 and 2.3 mA per V m^{-1} for a shod body. A range of expected currents is reported in the table where a range of measured field strengths is given or where the dominant frequency was known imprecisely.

Some of the ankle currents measured at the HF station were in agreement with the currents anticipated based on the measurements of electric field strength. However, the ankle currents measured at the MF station and on the VHF/UHF mast were generally less than the expected values. The disagreement between the predicted and measured values may have been due to several factors that were not controlled during the site visits. Time-variation in electric field strength and induced current was particularly acute at the AM transmitter stations and this made it difficult to record the electric field strength with the ankle current at a given instant. Any discrepancies may have been heightened by the different responses of the instruments to transient maxima since the electric field strength was measured using an analogue meter whilst limb currents were measured using a meter with a digital display.

The predicted values of ankle current were based on the assumption of plane-wave exposure with uniform intensity over the whole body. In reality, at most of the locations at the three sites where measurements were made, the strengths of the incident electric fields varied considerably over space. In many cases only the maximum field strength was reported and this would have given rise to a predicted ankle current greater than the measured value in circumstances where the spatial variation in field strength was substantial.

The numerical computations of ankle current were based on a voxel model of the body with a single fixed posture, standing upright with the arms down by the sides. Measurements of ankle current have been found to vary with the posture of the subject at different types of site, including AM transmitter stations and masts for VHF/UHF broadcasts. Whilst this would make the prediction of ankle current from a known electric field strength difficult for an arbitrary posture, most of the measurements reported in Table 19 were made for an upright individual with arms lowered.

Other factors that may have given rise to differences between measured and predicted ankle current were that the surface the individual was standing on may not have acted as a perfectly conducting ground plane. Also the footwear worn by the subject may not have had the same dimensions and dielectric properties as that assumed in the numerical model. Finally, the prediction of ankle current is particularly problematic on masts since the hands are frequently in contact with the conducting structure and this would influence the flow of current in the body.

Clearly there are many difficulties in relating electric field strength to ankle current under realistic exposure conditions and the results reported above do not provide a reliable validation of the numerical modelling that has been carried out. Measurements would have to be carried out under more rigorously controlled conditions in order to provide a verification of the results of computations. It would be of interest to know whether measurements of limb current provide a more reliable indication of whole-body SAR than measurements of electric field strength under arbitrary but realistic exposure conditions. At frequencies where heating of body tissues is predominantly ohmic, this might be expected to be the case. However, where exposure is non-uniform over space, there is greater opportunity for averaging body-absent measurements of electric field strength than there is for limb current. A spatially averaged series of measurements would be expected to provide a more reliable prediction of whole-body SAR than a measurement at a single position. A considerable amount of numerical computation would be required in order to address this issue on a theoretical basis.

Theoretical considerations aside, the practical limitation in measuring limb currents remains that meters have not been developed that are sensitive to frequencies in and above the UHF band. Consequently an epidemiological study cannot rely on induced current measurements if a proportion of the population to be studied are significantly exposed to ultra high frequencies. Another practical difficulty is that ankle current meters are often considered by personnel to be too heavy or cumbersome for wearing continuously, particularly when individuals are climbing or operating at height on a mast or tower. Furthermore there are no limb current meters available commercially with an automatic logging facility.

4 PERSONAL EXPOSURE INSTRUMENTATION

The spot measurements reported in the previous section demonstrate the difficulty in estimating exposures of workers to RF fields without recourse to personal exposure data since a broad range of exposures was found at the sites visited during the study. Electric and magnetic fields may be highly non-uniform and the exposures found at any given site could vary considerably depending on where the locations of measurement were with respect to antennas and other sources of exposure at the site.

Some radio sources transmit intermittently or with variable power and this creates additional difficulties in estimating exposures. The average duration of a transmission, number of transmissions per unit time and time-distribution of output power may not be constant and cannot be readily determined through spot measurements. Consequently, it is difficult to characterise the exposures of workers for epidemiological purposes through spot measurements alone, even with a detailed knowledge of the systems installed at sites where workers are exposed and of the locations at the sites where workers perform their duties. Personal exposure data are essential in allowing the variation of a worker's exposure over time to be established whilst carrying out typical duties at a particular site.

At the commencement of the study there were no commercially available RF personal exposure monitors with data-logging capabilities. Consequently a data logger was developed to interface with an existing personal monitor. The general principles of the operation of personal exposure monitors will be discussed before the specific instrumentation used in the study is described.

4.1 Personal exposure monitors

Personal exposure monitors (also known as dosemeters, although they do not strictly measure quantities of dose) are pocket-sized devices that are relatively inexpensive and are designed to be worn on the body. Traditionally, they contain two or three orthogonal electric dipoles and/or loops. Personal monitors are normally designed with a frequency response shaped to correspond with the field strength levels advised in a particular set of exposure guidelines, eg the ICNIRP reference levels (ICNIRP, 1999). An audible alarm or flashing LED is activated when the measured field approaches or exceeds the advised levels. Personal monitors do not provide a display of the measured field strength but data logging models are now available that sample field strength periodically and store the results for subsequent downloading.

The range of frequencies to which personal monitors respond has been extended in recent models by incorporating additional sensors in the devices. The Nardalert XT, manufactured by Narda Safety Test Solutions (Aslan, 2001), contains three independent sensors to give a specified range of 100 kHz to 100 GHz. The lower frequencies are detected using a surface charge sensor that responds to the radial fields produced by currents flowing in the body. Microwave frequencies are detected using thermocouple arrays. The detection of intermediate frequencies is complemented by a single dipole connected to a diode that responds to vertically polarised fields.

A major difficulty with attempting to assess compliance with guidelines using personal monitors arises because the instrument is worn close to the body whereas the field strength levels advised in the guidelines are body-absent levels. The perturbation of electric and magnetic fields by the body has been investigated under plane-wave conditions using computational techniques, employing a homogeneous numerical phantom to represent the human body (Schallner *et al*, 1998). Field enhancement was observed to be greatest at frequencies near body resonance and both the electric and magnetic fields could be increased by up to 13.5 dB. At other frequencies, enhancements of field strength between –20 dB and +10 dB were found to occur, depending on the direction of incidence and the polarisation of the radiation. Strong attenuation of the electric field did not generally coincide with strong attenuation of the magnetic field at any given frequency. A theoretical investigation of the electric and magnetic fields close to the body using a heterogeneous, anatomically accurate phantom has been carried out under this study and the results are reported in Section 5.1.

Compensation by personal monitors for the perturbation of the incident field by the body is generally done conservatively to ensure that exposures are not underestimated. Consequently the body-absent field strengths are likely to be overestimated under certain circumstances. Unreliable measurements will also occur if the direction of incidence is from behind the wearer since the body will shield the monitor from the field. The amount of shielding will depend on frequency and the location of the instrument on the body and will vary from person to person due to their different body sizes and tissue characteristics.

The accuracy of personal monitors will also be limited in situations where the field strengths are non-uniform over the body, such as in the near-field region close to antennas or near slot radiators, conducting structures and sources of RF leakage. Clearly a personal monitor worn on the torso may give a different response from one worn at head height in a non-uniform field. In some environments, personnel are frequently in motion and repeatedly change position and orientation with respect to the sources in their vicinity. This degree of dynamism would be expected to equilibrate the time-averaged field strength over different regions of the body. Consequently, in these circumstances, the time-averaged field strength measured using an instrument worn on the chest, for example, may provide a reasonable estimate of the time-averaged field strength over other parts of the body. However, some workers may be much more static with respect to the primary source of exposure, for example when sitting in a vehicle fitted with a mobile transmitter. In this case, the results obtained from a personal monitor worn at a fixed position on the body may not accurately represent the exposures of other regions on the body. It is common practice for personal monitors to be worn on the chest and it is often impractical to locate them adjacent to the head for comparison purposes.

4.2 Development of a personal exposure system

At the commencement of the study there were no commercially available RF personal exposure monitors with data logging capabilities. Consequently a data logger was developed to interface with the ESM-20 ‘RadMan’ personal monitor, originally produced by Wandel & Goltermann GmbH & Co, but now manufactured by Narda Safety Test Solutions. At the time, the ESM-20 was the only personal monitor with a communications port that allowed external control of the instrument and retrieval of data. The data logger is designed to connect to the dosemeter via a fibre-optic cable and store measurements of electric and magnetic field strength. The portable system was developed to allow it to be conveniently worn when working on a mast or tower, and is shown in Figure 7.

FIGURE 7 Data logger connected to an ESM-20 ‘RadMan’ personal monitor via a fibre-optic cable

It was general practice for the monitor to be worn in a breast pocket of the wearer’s outer clothing and for the data logger to be placed either in the opposite breast pocket or on the waist or, if the wearer was operating at height, in a kit bag attached to the individual’s harness. The fibre-optic cable could be run inside the clothing or harness to avoid snagging it on protruding structures whilst working.

The ESM-20 is a pocket-sized instrument with approximate dimensions 3 × 4 × 16 cm^3. Model BN2250/06 was used in the study and this incorporated a shaped frequency response to give the electric and magnetic field strengths as percentages of the respective reference levels advised by ICNIRP for occupational exposure. It should be emphasised that measurements made with the instrument were not carried out to investigate compliance with the ICNIRP guidelines but to obtain data for use in determining the feasibility of an epidemiological study of workers exposed to RF fields.

The ESM-20 has four LED indicators, which illuminate in turn when various percentages of the reference level for electric or magnetic field strength, whichever is the greater, are exceeded. There is also an audible alarm that is activated when 50% of the reference level is exceeded. The output of the monitor is proportional to the square of field strength with an upper limit of 126% of the field strength reference levels (160% of the equivalent power density levels). The sensitivity of the dosemeter is limited by its internal noise and this gives rise to a detection threshold in the region of 20–25% of the field strength reference levels. The specifications published by the manufacturer indicated that the ESM-20 is sensitive to electric fields with frequencies in the range 1 MHz to 40 GHz and to magnetic fields with frequency range 27 MHz to 1 GHz.

The data logger was built into a plastic case with dimensions 3 × 8 × 16 cm^3 and its weight was about 265 g. A push button on the side of the logger could be used to activate an event marker to tag the data being accumulated at that instant. After data collection, the information could be downloaded to a standard PC in plain ASCII format for subsequent analysis.

Two generations of data logger were constructed. The first-generation logger was designed to receive data from the personal monitor and calculate the average electric and magnetic field strength from 20 consecutive measurements of each. Once the calculations have been performed, the time, the average values of electric and magnetic field strength, the maximum field strength values, the event marker status and an error detection checksum are all written to a non-volatile memory in the logger. The averaging process then commences again and the cycle continues until the logger is switched off or the memory is full. The logger records data over a period of two seconds and writing the results to memory takes about 0.8 s; therefore the total period of the cycle is 2.8 s. The device can store up to 3624 sets of data, corresponding to a total logging period of about 170 minutes.

The second-generation logger has enhanced storage capacity and is known as the Megalog. The appearance of the Megalog is similar to that of the first-generation logger, however it does not feature an event marker. The Megalog samples electric and magnetic field strength every 0.6 s and the data are transferred to an eight-megabyte flash memory. The amount of data that can be stored is limited by the battery life rather than memory, and a single lithium PP3 battery provides over eight hours of running time. To extend the capability of the Megalog further, data collection can be paused, to allow the battery to be changed, and then resumed without loss of the information previously accumulated.

4.3 Extended-technology personal monitors

During the course of the study, Narda Safety Test Solutions started to market ‘extended technology’ personal dosemeters that incorporated data logging functions. The ESM-30 ‘RadMan XT’ is similar to the ESM-20 but it records the maximum, minimum and average values of electric and magnetic field strength over a pre-set averaging time. The device can store up to about 1600 sets of data and therefore does not have the capacity of the HPA-developed data logger.

More recently, the company has been marketing the Nardalert XT, shown in Figure 8, and this device has several advantages over the ESM-30 and ESM-20 plus data logger combination. The Nardalert XT is sensitive to a broader range of frequencies than the ESM-20/30, from 100 kHz to 100 GHz. The memory can store over 30000 measurements of electric field strength and the sampling rate can be programmed from 10 to 3600 measurements per hour. At the maximum sampling rate, the dosemeter can store eight and a half hours worth of data. One feature that the Nardalert XT does not share with the ESM-20/30 is that it does not employ magnetic field sensors.

FIGURE 8 Nardalert XT personal exposure monitor

The Nardalert XT has a broader dynamic range than the ESM-20 and it features both a reduced threshold of detection and an increased saturation level. Use of the Nardalert XT in the field has indicated that it responds to electric field strength at 10% of the ICNIRP reference level (equivalent to 1% of the power density reference level). The output of the Nardalert XT is an integer between 1 and 200 that represents the percentage of the equivalent plane-wave power density reference level advised by ICNIRP. Consequently the maximum electric field strength that can be measured is 141% of the corresponding field strength reference level.

An additional advantage that logging dosemeters have over the personal monitor/data logger combination is that the integrated instruments are less cumbersome and less prone to operational failure. It is clearly easier to wear a single pocket-sized device than to wear two instruments connected with a cable, particularly when working at height. The fibre-optic cable is susceptible to damage and could become disconnected from the data logger, unbeknownst to the wearer. Other problems that have been encountered with the data logger are the power switch sustaining damage or being inadvertently switched off through impact whilst the wearer was working on a lattice tower, and difficulties securing the logger to personnel when there are no pockets of sufficient size available in their clothing. A comparison of the data logging instruments discussed above is given in Table 20.

TABLE 20 Comparison of personal monitors with data logging capabilities. The letters E and H denote electric and magnetic fields respectively

Property	ESM-20 with data logger	ESM-20 with Megalog	ESM-30	Nardalert XT
Sensors	E and H	E and H	E and H	E
Frequency range (E)	1–40000 MHz	1–40000 MHz	1–40000 MHz	0.1–100000 MHz
Frequency range (H)	27–1000 MHz	27–1000 MHz	27–1000 MHz	–
Number of data sets	3624	>50000	1638	31263
Sampling interval	2.8 s[1]	0.6 s	1 s to 3 minutes[2]	1 s to 6 minutes[2]
Detection threshold[3]	6%	8%	8%	1%
Upper limit of detection[3]	160%	160%	160%	200%
Resolution[3]	0.6%	0.6%	0.6%	1.0%

[1] Average over and maximum from 20 consecutive measurements in a 2 s period

[2] Variable

[3] Expressed in terms of a percentage of the ICNIRP occupational reference level for equivalent plane-wave power density

5 EVALUATION OF PERSONAL EXPOSURE SYSTEM

5.1 Theoretical evaluation

The response of a chest-worn personal exposure meter to RF electromagnetic fields under a variety of exposure conditions was examined theoretically using the HPA computer model of an adult male, NORMAN (Dimbylow, 1997a). The investigation involved the calculation of field multiplication factors with respect to the electric and magnetic (E and H) components of an incident plane wave at points where the meter would be worn on the body.

5.1.1 Exposure conditions and calculations

NORMAN was stood vertically on a conducting ground plane and exposed to plane electromagnetic waves incident from his front, back and both sides. These four conditions are shown in Figure 9, together with the notation used to refer to each. In all four cases, the electric field vector was vertically directed so that the magnetic field vector was in the horizontal plane. Frequencies of 25, 50, 100 and 400 MHz were analysed and the electric field strength of the incident wave was 1 V m^{-1}.

A cuboidal volume of interest (VOI) was defined in front of one half of Norman's chest and this volume is shown in Figures 9 and 10. The volume had a width of 16 cm extending from the sternum to the left shoulder and a height of 20 cm extending downwards from the collar bone.

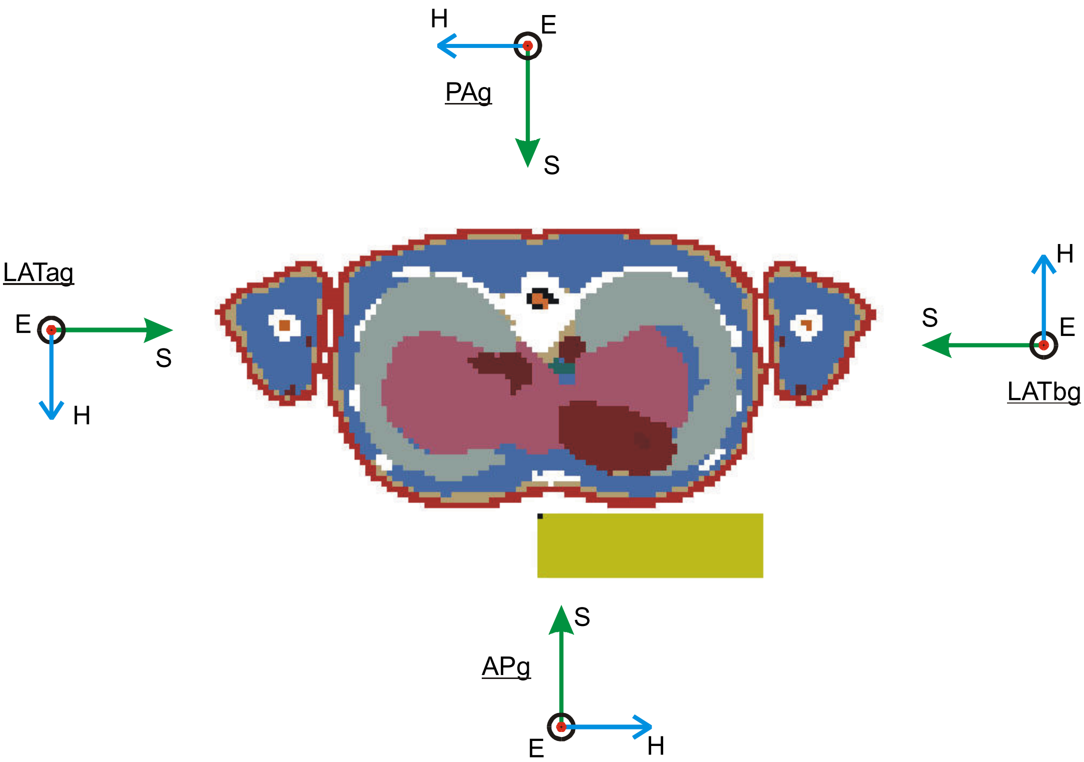

FIGURE 9 Cross-sectional view of NORMAN from above showing the volume in which the field distribution was examined and the four plane-wave exposure conditions

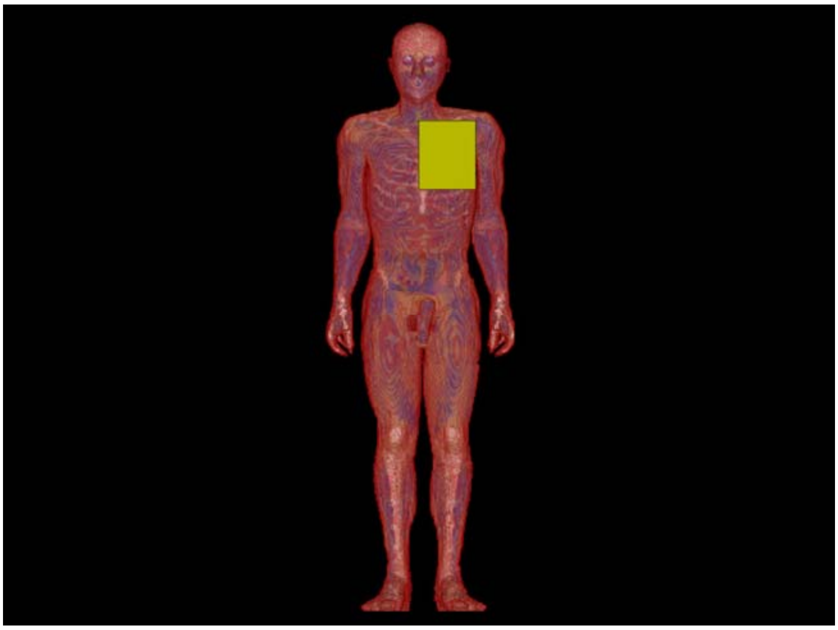

FIGURE 10 Front view of NORMAN showing the volume in which the field distribution was examined

A 4 mm resolution electromagnetic model was used for the calculations with frequencies of 100 MHz and above. In these cases, the VOI contained 6 planes parallel to the body front, each separated by a distance of 8 mm. Within each plane the electric and magnetic field strengths were calculated on a 4 mm grid. The plane nearest to NORMAN was separated by 4 mm at its closest point of approach.

For frequencies below 100 MHz, a 10 mm resolution electromagnetic model was used and the VOI contained only two planes; one at 10 mm from the closest part of the chest and the other at 20 mm. Within each plane, the electric and magnetic field strengths were then computed on a 10 mm grid.

The resulting electric and magnetic field strengths at points in the VOI were total fields arising from the summation of the field strengths in the incident plane wave with the fields scattered by the body due to its interaction with the plane wave. Hence, in order to determine the extent of the perturbation of the plane-wave by the body, the total field at each point was normalised to the field strength in the incident plane wave.

5.1.2 Results and interpretation

The minimum, maximum, average and standard deviation values for the normalised field strengths were calculated over the entire VOI for each frequency and plane wave condition. The results are shown in Tables 21 and 22, and then in Figures 11 and 12 for electric field strength and magnetic field strength respectively.

TABLE 21 Normalised electric field strengths calculated for the VOI for each frequency and plane wave incidence direction

		Normalised electric field strength			
Condition	Frequency (MHz)	Minimum	Maximum	Average	Standard deviation
APg	25	2.5323	4.0942	3.3722	0.3231
LATag	25	2.5175	4.0695	3.3534	0.3222
PAg	25	2.5918	4.1819	3.4427	0.3306
LATbg	25	2.6019	4.2002	3.4548	0.3313
APg	50	1.5690	2.3748	1.9425	0.1555
LATag	50	1.5572	2.3385	1.9185	0.1477
PAg	50	1.6388	2.4949	2.0428	0.1654
LATbg	50	1.6303	2.5076	2.0456	0.1734
APg	100	0.6139	1.0653	0.8380	0.0532
LATag	100	0.5853	0.9770	0.7644	0.0531
PAg	100	0.6200	1.2243	0.9096	0.0916
LATbg	100	0.5839	1.2163	0.9224	0.1171
APg	400	0.4233	1.1835	0.8282	0.1559
LATag	400	0.2134	0.9616	0.5795	0.1496
PAg	400	0.2667	0.5444	0.3761	0.0428
LATbg	400	0.1351	0.6571	0.3117	0.0860

TABLE 22 Normalised magnetic field strengths calculated for the VOI for each frequency and plane wave incidence direction

		Normalised magnetic field strength			
Condition	Frequency (MHz)	Minimum	Maximum	Average	Standard deviation
APg	25	2.2613	2.9616	2.6157	0.1557
LATag	25	2.2469	2.8755	2.5170	0.1426
PAg	25	1.7246	1.9396	1.8027	0.0527
LATbg	25	1.8755	2.5952	2.1421	0.1640
APg	50	2.2780	3.1259	2.7336	0.1862
LATag	50	2.1061	2.9509	2.5075	0.1964
PAg	50	0.8028	1.3015	1.0084	0.1315
LATbg	50	1.3366	2.4452	1.7916	0.2860
APg	100	2.0576	2.7818	2.3967	0.1281
LATag	100	1.4630	2.3430	1.9375	0.2118
PAg	100	0.2813	1.1980	0.6838	0.2288
LATbg	100	1.0251	2.0502	1.4379	0.1957
APg	400	1.1200	1.8957	1.3855	0.1216
LATag	400	0.7277	1.5320	1.0233	0.1475
PAg	400	0.1272	0.8577	0.4053	0.1748
LATbg	400	0.5787	1.2293	0.8509	0.0949

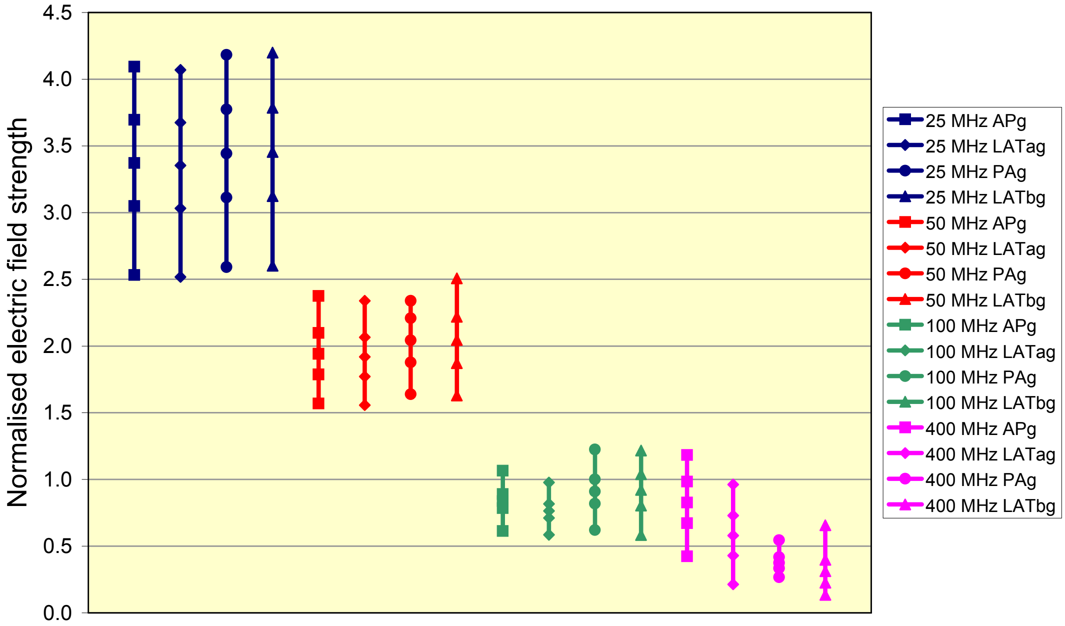

FIGURE 11 Electric field strength in the VOI for each of the 16 exposure conditions described in terms of the minimum, average−standard deviation, average, average+standard deviation and maximum

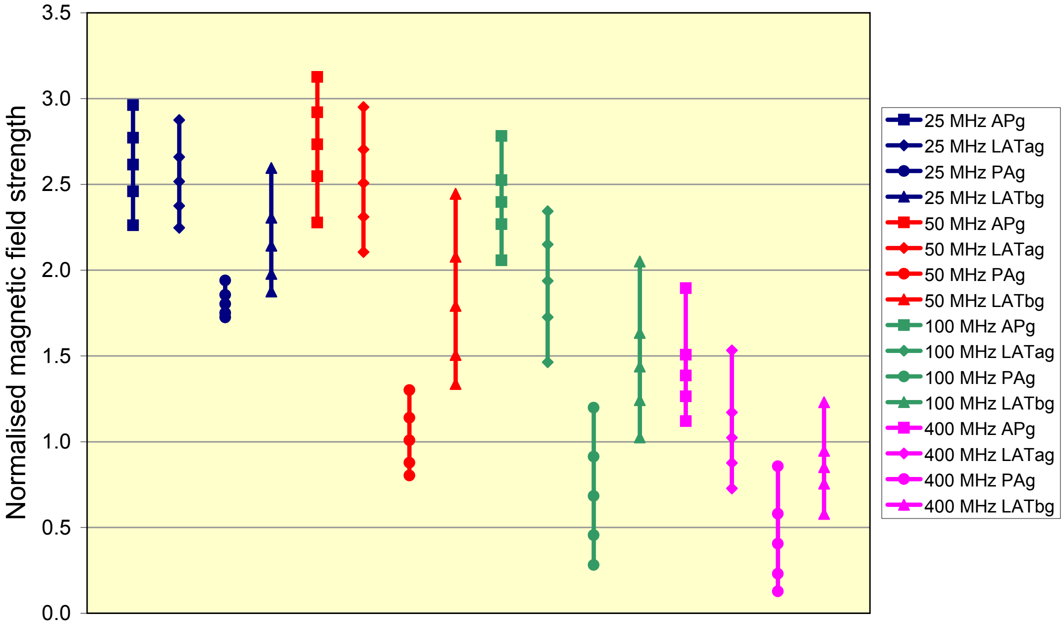

FIGURE 12 Magnetic field strength in the VOI for each of the 16 exposure conditions described in terms of the minimum, average−standard deviation, average, average+standard deviation and maximum

The average electric field strength in the VOI is enhanced by a factor that increases as frequency reduces below 100 MHz, whereas it is generally somewhat reduced for 100 MHz and above. This enhancement was due to the component of the electric field normal to NORMAN's chest becoming large in relation to the incident vertically directed 1 V m^{-1} electric field. Currents flowing vertically up and down NORMAN produce the normal component of the electric field, and these would be greatest at the body resonance of 35–40 MHz.

The average electric fields in the VOI are not greatly sensitive to the direction of wave incidence for low frequencies and they are within 2.5% at 25 MHz. Sensitivity increases with frequency so that the averages are within 7% at 50 MHz, within 20% at 100 MHz, but only within 160% at 400 MHz. This increasing sensitivity to direction of incidence with frequency is because the penetration depth of the waves in the body reduces leading to a greater degree of shadowing for waves from behind. It clearly has a major effect on the accuracy of personal monitors when used for frequencies above 100 MHz.

Ignoring the effect of directionality, the absolute range of electric field strengths in the VOI is within ±25% about the average field strength for 25 and 50 MHz and the standard deviation represents less than 10%. The range of field strengths is greater for higher frequencies at ±35% for 100 MHz, while the standard deviation is up to 13%. At 400 MHz, the range of field strengths in the VOI is much greater, it being within +110% and -60% with a standard deviation of up to 30%.

The most obvious difference between the magnetic field results and the electric field results concerns the sensitivity of the magnetic fields in the VOI to direction of wave incidence. Shadowing has a much greater effect than with electric fields so that, even at the least sensitive frequency of 25 MHz, the wave incident from the back (PAg) gives an average magnetic field strength 30% lower than a wave incident from the front (APg).The magnetic field strength in the VOI is progressively more enhanced with reducing frequency and the enhancement factor rises to around 2.5 at 25 MHz, ignoring the effects of incidence direction.

The results of the assessment agree qualitatively with the findings of Schallner *et al*. (1998) who also found the greatest enhancement of electric and magnetic field strength at the body resonance under AP and LAT illumination when the electric field was vertically polarised. At frequencies above the body resonance, the authors found the magnetic field strength more greatly enhanced than the electric field strength and this also agrees with the results reported above. The maximum enhancement of electric field strength noted by Schallner *et al*. was a factor of 3.5 for both AP and LAT orientations and this factor is in good agreement with the results shown in Figure 11. However, the enhancement of magnetic field strength by a factor of 4.7 at body resonance under AP illumination, again with vertical polarisation, reported by the German authors is greater than the maximum enhancement determined using NORMAN. One possibility for the discrepancy is that there were several differences between the phantoms used in the two assessments. NORMAN is an anatomically accurate heterogeneous phantom and the various body tissues of which the phantom is composed were assigned realistic values of conductivity and permittivity. The assessment was carried out with NORMAN oriented vertically on a ground plane. The phantom used in the earlier study comprised a conducting surface that was less anatomically accurate and it was isolated rather than grounded. Given these differences the level of disagreement between the two assessments is not surprising.

5.2 Existing personal monitor calibrations

The personal monitors used during the project (the Nardalert XT and ESM-20, see Sections 4.2 and 4.3) were supplied with calibration certificates by the manufacturer, however it was not stated whether these calibrations were for the instruments in free space or mounted on the body. Therefore, the instrument responses were compared with the response of another broadband probe having a calibration known to be for free space conditions.

The reference instrument with a free-space calibration was a Holaday Instruments 6005 probe and this was set up in an EMCO GTEM cell with a variable input power and frequency. The calibration was traceable to national standards with an uncertainty of ±1 dB.

For a range of frequencies, the power input to the GTEM cell was set to give an E-field reading on the HI-6005 equal to 50% of the ICNIRP guidelines. Each personal monitor was then substituted in place of the HI-6005 and its indicated field level was noted. The results are shown in Figures 13 and 14.

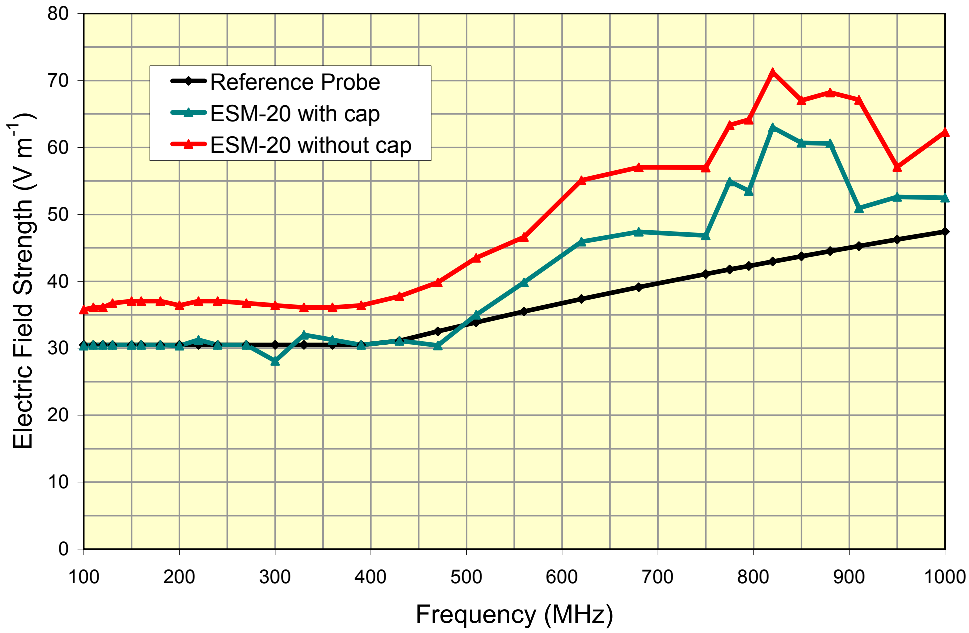

FIGURE 13 Comparison of E-field reading from a ESM-20 mounted vertically inside a GTEM cell with the reading from a reference instrument

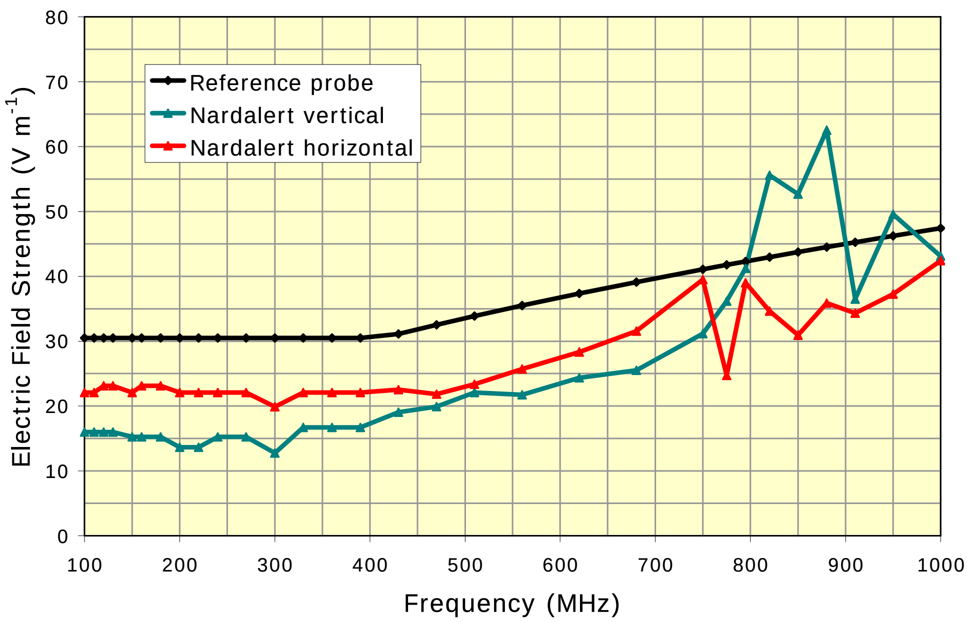

FIGURE 14 Comparison of E-field reading from a Nardalert XT mounted vertically and horizontally inside a GTEM cell with the reading from a reference instrument

The ESM-20 would normally be used with its cap and these results are shown in Figure 13. The figure shows good agreement between the ESM-20 reading and that of the reference instrument, at least for frequencies up to 500 MHz, indicating that the instrument was probably calibrated in free space rather than mounted on the body.

The results for the Nardalert in Figure 14 show it reading around 50% of the reading with the reference instrument when it is mounted vertically, as it would be on the body, for frequencies up to around 700 MHz. This could indicate that the manufacturer has designed the Nardalert to account for the field enhancement that occurs near the body for low frequencies up to around 100 MHz (see Figure 11), however, given that the enhancement is not present above 100 MHz accuracy would not be improved across the spectrum.

In conclusion, there is a need to account for the presence of the body in the calibration of personal monitors. Computer modelling of the fields close to the body would allow a correction factor to be developed for plane-waves incident on the front of the body across the spectrum. Such a calibration would still not be reliable for plane waves incident from other directions at frequencies much above 100 MHz because of the effect of shadowing by the body.

5.3 Inter-comparisons of instrumentation under real exposure conditions

Inter-comparisons of instrumentation have been carried out at a number of broadcast, telecommunications and radar sites under exposure conditions that were considered typical of normal operation. The purpose of some of the inter-comparisons was to compare the electric and magnetic field strengths recorded using portable survey meters with results obtained with the body-worn ESM-20 personal monitors and data logger units. The remaining inter-comparisons were carried out between the ESM-20 and Nardalert XT personal exposure monitors.

The personal monitors had responses shaped to the reference levels advised by ICNIRP for occupational exposure, whereas the portable survey meters used in the study did not have shaped responses. Consequently, assumptions had to be made about the frequencies being transmitted from each site in order to perform the first set of inter-comparisons. The procedure was straightforward at sites where exposure was assumed to be dominated by VHF transmissions since the ICNIRP reference levels are independent of frequency from 10 MHz to 400 MHz. Consequently the response of the ESM-20 is assumed to be flat within this frequency range and the results can be readily converted to field strength. At frequencies below 10 MHz and in the range 400 MHz to 2000 MHz, the reference levels vary with frequency. At sites where exposures were considered to be dominated by frequencies in these ranges, a single representative frequency was selected and field strengths were calculated from the data obtained from the ESM-20 on the assumption that the exposure was entirely due to this one frequency. The results from the inter-comparisons are discussed below.

5.3.1 Inter-comparison between portable survey meters and ESM-20

5.3.1.1 VHF/UHF broadcast site

An inter-comparison of electric field instrumentation was made at a single high-power broadcast site transmitting in the VHF and UHF bands. The procedure was carried out on a platform between arrays of VHF and UHF antennas, towards the top of the tower on which the antennas were mounted. Two portable survey meters were compared with each other and with a body-worn ESM-20 personal monitor, connected to a data logger. The two survey meters were (i) a Wandel & Goltermann EMR-200 field strength meter connected to a Type 8 isotropic electric field probe and (ii) a Holaday HI-4417 Portable RF Survey System. The sum of uncertainties given by the manufacturer of the HI-4417 is ±2.5 dB. The accuracy of the EMR-200 would be expected to be similar.

Nine measurement positions were chosen and these were at three heights on the vertical axis mid-way between each leg of the supporting structure and the wall of the steel cylinder that surrounded the platform. The field strengths indicated by the two survey meters varied with time by up to 20 V m^{-1} at each location, therefore the maximum reading observed during a period of about 15 seconds was recorded for each location. The results are given in Table 23. The results indicate an agreement between the two meters generally within 1.5 dB. The largest discrepancy of 2.4 dB is within the manufacturers' specifications for the instruments.

In addition to the measurements using the portable survey meters, an individual wearing the ESM-20 and data logger stood for 60 seconds mid-way between each leg of the structure and the wall. The individual stood facing tangentially with respect to the cylinder for the first 30 seconds, and then radially, ie towards the leg, for another 30 seconds. The exposure indices recorded from the personal monitor were converted to electric field strength using the formula provided by the ICNIRP guidelines, assuming a frequency of 600 MHz. The average and maximum electric field strengths over each 30-second period are given in Table 24.

TABLE 23 Electric field strength recorded by portable survey meters

Position	Height above platform floor (m)	Electric field strength (V m^{-1})		Difference (dB)
		EMR-200	HI-4417	
Leg A	0.1	90	103	1.2
	1.0	75	82	0.8
	1.8	60	79	2.4
Leg B	0.1	85	95	1.0
	1.0	75	85	1.1
	1.8	78	78	0.0
Leg C	0.1	78	78	0.0
	1.0	55	65	1.5
	1.8	67	57	1.4

TABLE 24 Electric field strength calculated from logged data

		Electric field strength (V m^{-1})	
Position	Orientation	Average	Maximum
Leg A	Tangential	40	48
	Radial	37	53
Leg B	Tangential	52	66
	Radial	37	62
Leg C	Tangential	35	52
	Radial	48	57

The results reflect the observation that the electric field strength varied with time since the maximum field strengths recorded were up to 25 V m^{-1} greater than the average field strengths. There did not appear to be a general trend for the field strength to be greater for one orientation of the individual with respect to the other. The maximum field strengths were generally lower than the maximum field strengths measured using the portable survey meters, however the disagreement was within that permitted by the manufacturers' specifications of uncertainty.

5.3.1.2 Telecommunications site

An inter-comparison of electric-field instrumentation was made at one telecommunications site. The inter-comparison was not detailed and was intended to provide a broad indication of the agreement between portable survey meters and personal monitoring equipment. A tower was located at the site and on it were mounted antennas associated with base stations for wide-area paging and mobile telecommunications. It was considered that the pager base stations gave rise to the greatest exposures on the tower.

The portable survey meter used during the site visit was a Wandel & Goltermann EMR-300 field strength meter connected to a Type 8.2 isotropic electric field probe. The instrument was used to measure electric field strength close to the ladder at the position where the body of an individual would be situated when climbing the ladder. Measurements were made towards the top of the tower at heights close to those at which the paging antennas were mounted. The field strength was found to vary with height and over time. The maximum field strengths recorded over a period of time ranged from 14 V m^{-1} to 22 V m^{-1}, depending on elevation.

The ESM-20 personal monitor was worn by an individual who spent six minutes on the ladder in the region where the measurements had been made using the portable survey meter. The exposure indices were converted to electric field strength under the assumption that exposures were entirely due to VHF transmissions. The personal exposure record exhibited a variation with time, as expected from the spot measurements, and the maximum value recorded over each 2.8 second sampling period was generally in the range 8–22 V m^{-1}, although extreme values of 7 V m^{-1} and 51 V m^{-1} were registered. The range of field strengths typically encountered is in broad agreement with the field strengths measured using the portable survey meter.

5.3.1.3 Rooftop site

An inter-comparison of electric-field instrumentation was made at one rooftop site. A number of VHF and UHF radio systems were installed at the site and the purposes of most of the systems were unknown. However, it was established that some of the VHF systems were base stations for wide-area paging. The portable survey meter used during the site visit was a Holaday HI-4417 Portable RF Survey System. The instrument was used to measure electric field strength at a number of locations close to the protective steel barrier that had been installed around the perimeter of the roof. The locations chosen were generally at positions where local maxima in the electric field had been detected.

Following the measurements using the portable meter, the individual wearing the ESM-20 stood near the barrier such that the personal monitor was in approximately the same position as that in which the probe of the portable survey system had been. Measurements were recorded using the ESM-20 and data logger for periods of several minutes at each measurement location.

The field strengths measured using the portable survey meter and the personal monitor were found to vary over time and the results are summarised in Table 25. The average and maximum electric field strength recorded at each location by the data logger are listed in the table, where exposure indices have been converted to field strength under the assumption that exposures were entirely due to VHF transmissions. Where a range of values is reported for the portable survey meter, this indicates the time-variation of electric field strength at the specified location. A single reported value corresponds to the maximum measured field strength.

TABLE 25 Electric field strength measured using a Holaday HI-4417 portable survey meter and an ESM-20 personal monitor

		Electric field strength (V m^{-1})		
Location	Description	ESM-20 (average)	ESM-20 (maximum)	HI-4417
1	Leaning against barrier	36	55	65
	Standing with back to barrier	22	45	25–36
2	Leaning against barrier	41	>70	>300
3	0.5 m from barrier	34	58	40–50
4	0.5 m from barrier	19	31	20
5	Leaning against barrier	19	31	50
6	Leaning against barrier	18	33	120–170
7	Standing with back to barrier	22	45	50
	Leaning against barrier	28	68	160–190
8	0.4 m from barrier	32	63	44–54

The electric field strengths recorded by the ESM-20 and data logger were found to be in broad agreement with the measurements taken using the portable survey meter at locations where the field strength did not exhibit strong spatial variation. In contrast, at locations where the electric field was highly non-uniform, particularly when very close to the protective barrier, the personal monitor underread with respect to the portable meter.

The reasons for the discrepancies are likely to be largely due to distortion of the field by the individual wearing the personal monitor and differences in the positioning of the two instruments. The portable survey meter could be used to locate a highly localised maximum electric field strength close to the barrier, however it was not possible for the individual wearing the personal monitor in his breast pocket to be certain that the sensor of the monitor was in the precise location of maximum field strength. Moreover, the perturbation of the electric field by the body of the individual is likely to have resulted in a change to the position and magnitude of the maximum field strength.

5.3.2 Inter-comparison between personal exposure monitors

5.3.2.1 VHF broadcast site

An inter-comparison between the data recorded by ESM-20 and Nardalert XT personal monitors has been carried out at a single VHF broadcast site. Some UHF telecommunications antennas were also mounted on the tower at the site, however the exposures were considered to be predominantly due to the VHF systems. The two instruments were worn by the same individual, the ESM-20 was positioned on the right hand side of the waistband of the wearer’s harness and the Nardalert XT was positioned at the corresponding location on the left hand side of the waistband. The subject climbed to near the top of the 110 m tower, lingering on most of the platforms on the way up. The individual spent some time on the upper platforms, where the exposures were highest, and then descended the tower.

The electric field strengths recorded by the two instruments are shown overlaid in Figure 15. The index of exposure on the ordinate axis of the plot is defined as the percentage of the reference level of electric field strength given by ICNIRP for occupational exposure, chosen because the data were output in this form rather than as actual field strengths. The background level in the region of 20–25 units in the ESM-20 trace was due to noise intrinsic to the instrumentation and was not an indication of ambient exposure. The data recorded by the Nardalert at times outside the period of time spent on the upper platforms of the tower (between approximately 14:05 and 15:00) were largely below the noise floor of the ESM-20. This suggests that treating data in the noise at face value could result in a significant overestimation of time-averaged exposure when using the ESM-20.

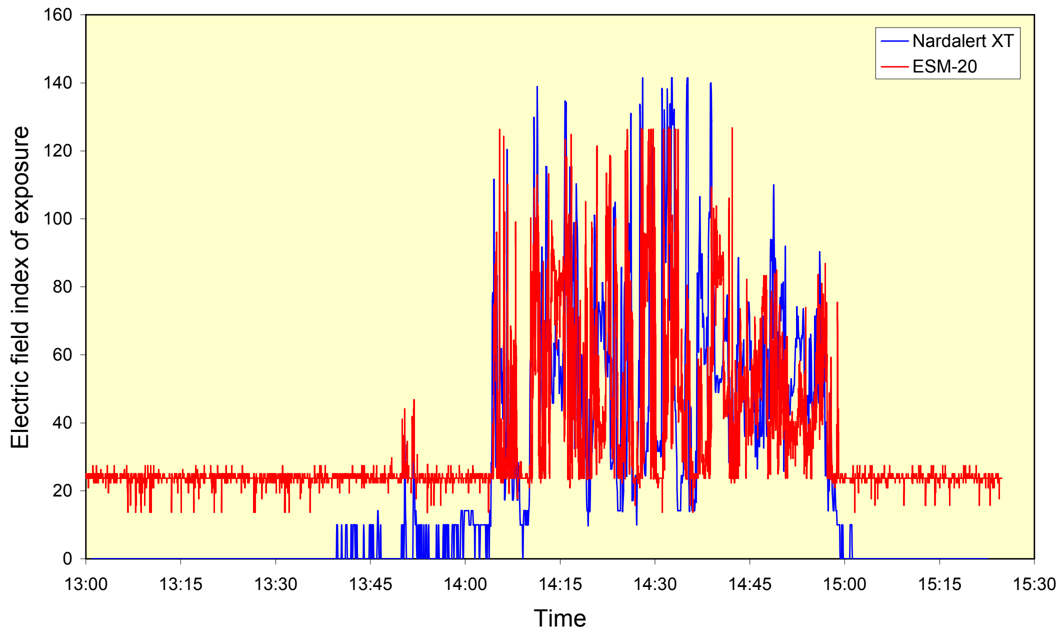

FIGURE 15 Comparison of electric field strengths recorded by an ESM-20 and a Nardalert XT at a broadcast site

The two dosemeters had different lower and upper limits of detection and different sampling intervals. Given this and the non-normal distribution of data, a direct comparison between the two plots of electric field strength using a statistical analysis is not straightforward. However, several parameters have been extracted from the portions of data corresponding to the period of time during which the individual was on the tower and these are shown in Table 26. The table includes a second column for the ESM-20 where the 'censored data', ie the data in the noise floor, have been treated statistically. The statistical treatment was performed using the semi-parametric, or 'robust' method of Helsel (1990) and was applied using version 4.0 of UnCensor, a software program developed at the University of Georgia, Savannah River Ecology Laboratory. Further detail of the statistical treatment of censored data in the study can be found elsewhere (Cooper *et al*, 2004).

TABLE 26 Comparison between an ESM-20 and a Nardalert XT at a broadcast site

Parameter	ESM-20	ESM-20 (statistical analysis)	Nardalert XT
Mean exposure index	33.8	29.0	21.4
Mean square of exposure index	15.4	13.5	14.9
Percentage of time exposure index >30	27.3%	27.3%	29.1%
Percentage of time exposure index >50	15.5%	15.5%	19.3%
Percentage of time exposure index >75	7.3%	7.3%	8.1%

The results obtained from the data captured using the Nardalert XT generally agreed with those obtained using the ESM-20 to within ±3 dB. The only exception to this observation was found when the mean exposure indices were compared without treating statistically the noise from the exposure record obtained using the ESM-20. In this instance the mean exposure index of 33.8 from the ESM-20 data was 4 dB greater than the value of 21.4 obtained from the Nardalert XT data and confirms the overestimation of exposure from the ESM-20 data, as discussed above. Results are shown in Table 26 of the percentage of time that the individual was exposed at indices greater than the three arbitrary values of 30, 50 and 75. All three percentages were found to be greater when evaluated from the Nardalert XT data than when evaluated from the ESM-20 data.

5.3.2.2 Telecommunications site

An inter-comparison between the data recorded by the ESM-20 and Nardalert XT personal monitors has been carried out at a telecommunications site at which a number of VHF and UHF radio systems were installed. Microwave dish antennas supporting point-to-point links were mounted on the tower at the site, however the purposes of a number of other antennas, also mounted on the tower, were unknown. The two instruments were worn by the same individual and were positioned on the same side of his harness. Portions of the electric field strengths recorded by the two instruments are shown overlaid in Figure 16. Few of the observations in the Nardalert XT exposure record exceeded the noise floor of the ESM-20 monitor.

A direct comparison between the two plots of electric field strength is not straightforward since there are too few uncensored data in the ESM-20 trace to allow a statistical treatment. However, several parameters have been extracted from the data and these are shown in Table 27. The second column for the ESM-20 is where the observations have been substituted with the value zero at all times when the noise floor of the instrument was not exceeded.

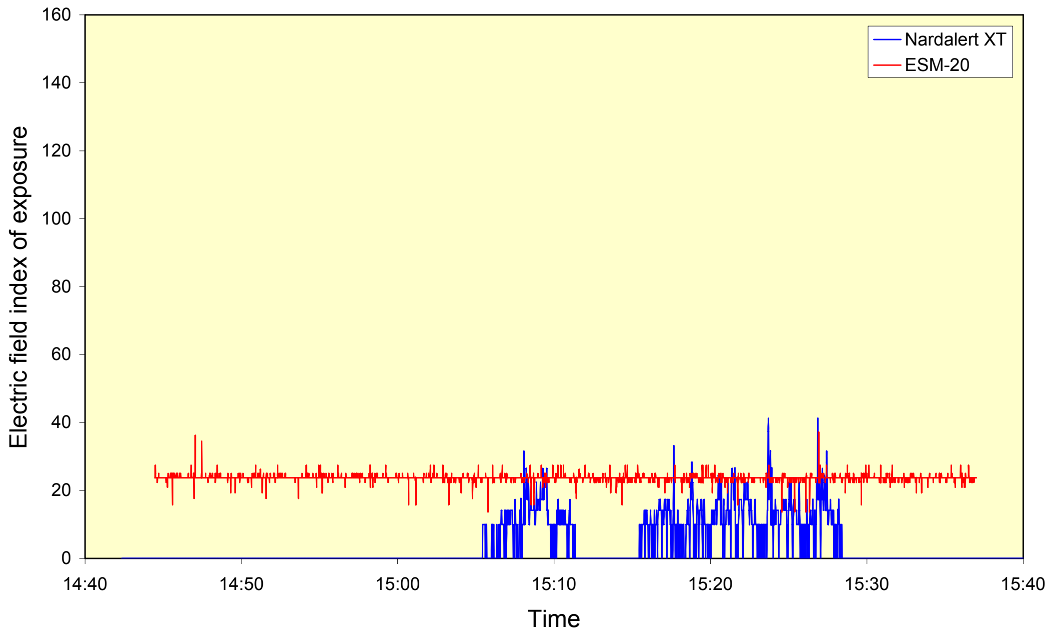

FIGURE 16 Comparison of electric field strengths recorded by an ESM-20 and a Nardalert XT at a telecommunications site

TABLE 27 Comparison between an ESM-20 and a Nardalert XT at a telecommunications site

Parameter	ESM-20	ESM-20 (data in noise treated as zero)	Nardalert XT
Mean exposure index	23.6	0.0	7.0
Mean square of exposure index	5.6	0.0	1.1
Maximum exposure index	37.1	37.1	41.2
Percentage of time exposure index >30	0.1%	0.1%	0.4%

The results obtained from the data captured using the Nardalert XT were generally not in good agreement with those obtained using the ESM-20. The only exception to this observation was found when the maximum exposure indices were compared with each other, where the two values differed by 0.9 dB. The remaining calculated values suggest that treating the data in the noise floor at face value could result in a significant overestimation of mean exposure when using the ESM-20. Conversely, reassigning the data in the noise the value zero could result in a significant underestimation of mean exposure. Clearly this situation is worst in circumstances where there are very few observations above the noise floor. In situations where most of the observations are above the noise, a better agreement between the results obtained using the ESM-20 and those obtained using the Nardalert XT would be expected, as found for the inter-comparison at the broadcast site, described above.

One of the parameters examined in Table 27 was the percentage of time that the individual was exposed at indices greater than 30 (this value was chosen because it was just above the noise floor of the ESM-20). The percentage was found to be greater when evaluated from the Nardalert XT than when evaluated from the ESM-20 data. This accords with the trend that was observed at the broadcast site.

5.3.2.3 Radar site

An ESM-20 and a Nardalert XT were worn by an individual at a radar site and both monitors were worn on the front of the body. The electric field strengths recorded by the two instruments are shown in Figure 17. Field strengths above the detection threshold of the Nardalert XT were measured between 15:09 and 15:19, corresponding to the time the wearer was on the aerial platform, just beneath the antenna at the site. Field strengths above the lower limit of detection of the ESM-20 were also measured between 15:09 and the end of the exposure record at 15:13. The period 15:09–15:14 is expanded in Figure 18.

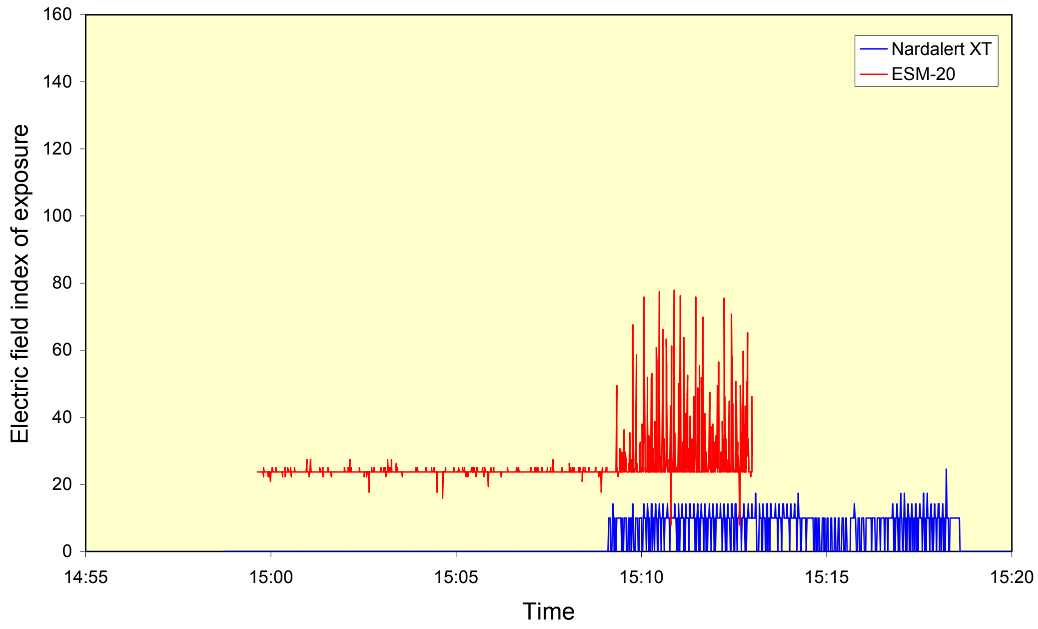

FIGURE 17 Comparison of electric field strengths recorded by an ESM-20 and a Nardalert XT at a radar site

For much of the period shown in Figure 18, the Nardalert XT trace clearly shows a peak every 6 s and this interval corresponds to the rotation period of the antenna. The ESM-20 trace appears to be more erratic and the peaks are less regularly spaced, although there is evidence of a 6 s cycle at certain times. There is a clear discrepancy between the field strength measured using the ESM-20 and that measured using the Nardalert XT since the peak exposure indices in the Nardalert trace are typically 14 whereas the peak indices in the ESM-20 trace are generally in the range 40–80. At no time did any of the data points in the Nardalert XT trace exceed the detection threshold of the ESM-20.

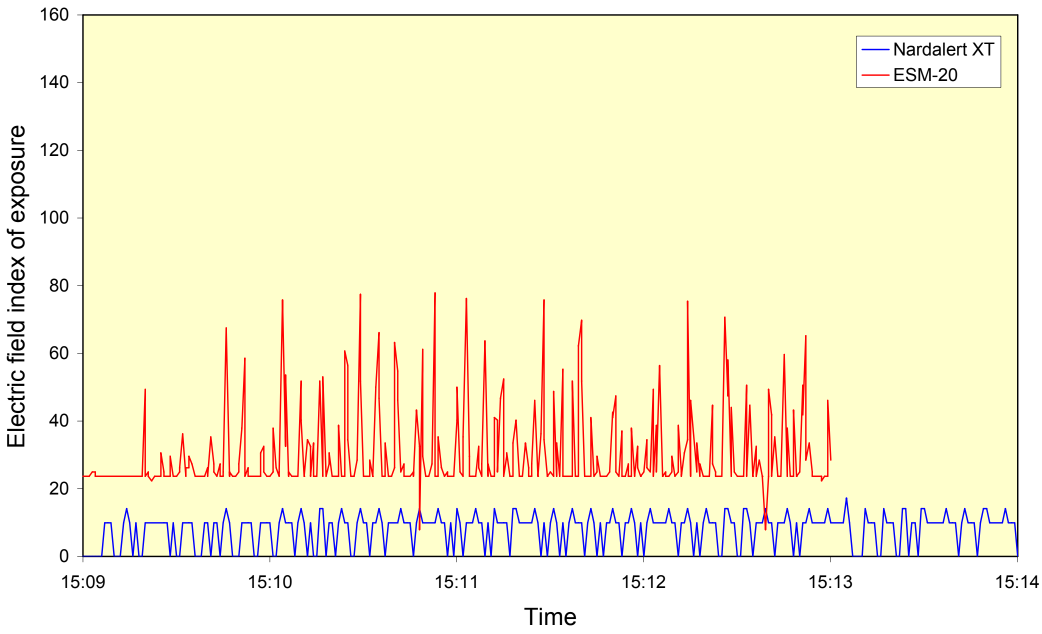

FIGURE 18 Comparison of electric field strengths recorded by an ESM-20 and a Nardalert XT at a radar site

The disparity between the two traces may be due to the different characteristics of the detectors deployed by the instruments since the ESM-20 uses a diode detector whereas the Nardalert XT incorporates a thermocouple detector for frequencies above 1 GHz. Thermocouple detectors generally give a stable response to pulsed fields and display the true rms field strength from a stationary radar, hence there is little variation in the peak exposure index for each antenna rotation in Figure 18. However, thermocouple detectors tend to feature longer integration times than diode detectors and this can lead to inaccurate results when the radar antenna is rotating, if the integration time is longer than the illumination time. The data in Figure 17 show that the Nardalert XT consistently displayed lower values than the ESM-20 and this indicates that the maximum readings obtained with the former instrument may have been less than the rms value from a stationary antenna.

The integration time of the fast version of the ESM-20, used in the study, is specified by the manufacturer at 30 ms and this is not likely to materially exceed the illumination time of the rotating antenna in the near field. Consequently the maximum field strength measured by the ESM-20 on the aerial platform is likely to be indicative of the rms field strength under illumination from a stationary antenna, subject to the uncertainties associated with the diode response, as discussed previously. The erratic trace produced by the ESM-20 may have been due to the long ‘dead time’ between sampled data when used with the Megalog data logger. Since the integration time is 30 ms and data are stored, on average, every 620 ms there is a dead time of 590 ms between samples. The radar antenna rotated a nominal 35° within this time, hence it is possible that during some rotations the main beam could be swept past the detector in between two consecutive samples. Clearly the detector could be sampling whilst being illuminated by different parts of the radiation pattern with each rotation of the antenna and this would lead to the trace being more erratic than that from a thermocouple detector, as observed in Figure 18. The use of personal exposure monitors, like that of portable survey meters, for the quantification of exposures to the emissions from rotating radar antennas is clearly problematic.

6 CONCLUSIONS

A number of compact, lightweight hazard survey meters for the measurement of electric and magnetic field strengths have been placed on the market in recent years. These have been found convenient for use in most of the environments encountered during the course of the study and are much better suited for use at height on masts and towers than older bulkier instruments. Portable survey meters have been found useful for making spot measurements of electric and magnetic field strength in order to provide information on the range of exposures encountered at different types of site. Electric field meters have been used at many sites to measure the strengths of fields with frequencies ranging from tens of kilohertz to tens of gigahertz. The use of magnetic field meters has been more limited since the equipment available to the study did not respond to frequencies greater than 300 MHz.

A suite of limb current meters, based on current transformers, has been developed which respond to frequencies up to 250 MHz. Measurements of ankle current in the field were often less than the induced currents that would be expected based on measurements of electric field strength and theoretical dosimetric data, assuming plane wave conditions. Factors affecting the results include non-uniformity of the electric fields, grounding conditions, contact currents and the responses of meters to the time-variation of incident fields. Although limb current meters can be conveniently used for spot measurements at height, they are too heavy or cumbersome for continuous monitoring of exposure.

Spot measurements of electric and magnetic field strength and limb current have been made at sites used for broadcast, telecommunications and air traffic control. The range of exposures found at the various sites was very broad. For example, the maximum electric field strength was observed to range from a few volts per metre at some sites to several thousand volts per metre at a VLF/LF transmitter station.

Field strengths were measured at a number of masts and towers supporting antennas for VHF and UHF broadcast transmitters. Exposures were largely in the near field and close to conducting structures, therefore field strength was not uniform over the region occupied by the body in many circumstances. Ambient levels of electric field strength up to 100 V m^{-1} were found at locations tens of centimetres away from the nearest conducting structures at high-power broadcast sites. Stronger electric fields were recorded in highly localised regions closer to antennas, feeders, splitters and other structures.

Field strengths on masts, towers and rooftops supporting telecommunications antennas were generally lower than field strengths at broadcast sites where the transmitted powers could be substantially greater. The strongest electric fields were found in the vicinity of antennas associated with base stations for wide-area paging and ambient levels of tens of volts per metre were recorded. Field strengths in the near field and close to metallic antenna supports could be greater, however these would not represent whole-body exposure. Electric field strengths close to GSM antennas were less than 25 V m^{-1} at all locations, except for some regions directly in front of the antennas where the fields could be stronger.

The highest electric and magnetic field strengths measured inside buildings at MF and HF AM transmitter stations were in localised regions close to transmitter units. These field strengths reduced rapidly with distance so would be unlikely to contribute significantly to the time-weighted average exposure of workers. The strongest fields measured at AM stations were found outdoors close to antennas, feeders and switches. In many cases there was considerable variation in field strength with height above the ground, with time and with distance from the relevant source.

There were practical difficulties in making measurements at radar sites due to the pulsed signals and the rotating antennas. Mean electric field strengths at most locations readily accessible to personnel were no more than a few volts per metre. Electric field strengths at satellite earth stations could be a few tens of volts per metre close to antennas but, more generally, they were below the detection thresholds of portable survey instrumentation.

Despite the versatility of modern instrumentation, it is difficult to characterise an individual worker's exposure through spot measurements alone due to the considerable variation in exposure with time, over space and at different locations in many RF environments. The difficulties with estimating exposures are compounded in situations where the radio sources transmit intermittently or with variable power.

Data-logging personal exposure monitors are an attractive option for exposure assessment in epidemiological studies since they measure field strength periodically and store the data. Personal exposure monitors are compact, lightweight and interfere little with normal working routines. Moreover personal exposure monitors incorporate a frequency response that is based on recommended guideline levels, derived from dosimetric data, and provide a rational means of comparing exposures at different frequencies.

Data loggers have been developed for use with the ESM-20 'RadMan' personal exposure monitor. The first generation data logger recorded the average and maximum electric and magnetic field strengths from twenty consecutive measurements over a period of 2 s. The results were stored every 2.8 s and the capacity of the device allowed the storage of nearly three hours worth of data. The second generation logger, known as the Megalog, had a greater memory; it sampled electric and magnetic field strength every 0.6 s and could run continuously for an entire working day.

A theoretical assessment of the effects of perturbation of electromagnetic fields and shadowing by the body on the accuracy of personal exposure monitors worn on the body has been undertaken. The direction of incidence had a major effect on the accuracy of the electric field strength measurements for frequencies above 100 MHz. The measurement of magnetic field strength appeared to be sensitive to the direction of incidence at frequencies in both the HF and VHF bands. There is a need to account for the presence of the body in the calibration of personal exposure monitors since this was found to enhance both the electric and magnetic field strength in front of the chest at frequencies close to the frequency of body resonance. Computer modelling of the fields close to the body would allow a correction factor to be developed for plane-waves incident on the front of the body across the spectrum. Such a calibration would still not be reliable for plane waves incident from other directions at frequencies much above 100 MHz because of the effect of shadowing by the body.

Electric fields were investigated at several sites using both portable survey equipment and personal exposure monitors. The electric field strengths measured using the two types of equipment generally agreed to within manufacturers' specified uncertainties when the user was facing towards the source of exposure, providing the measurement location was not in a region where the spatial distribution of the field was highly non-uniform. Discrepancies between the results from the two types of instrumentation were found near antennas and other conducting structures when field strength maxima were highly localised in space. In these circumstances, the body-worn ESM-20 was capable of significantly underreading the field strength, compared with portable survey instrumentation. This may have been largely due to perturbation of the field caused by the presence of the body which could have resulted in a shift in the magnitude and position of the maximum electric field strength.

The exposure measurements obtained using a Nardalert XT personal monitor at broadcast, telecommunications and radar sites were largely below the noise floor that limits the detection threshold of the ESM-20. This suggests that treating the data in the noise at face value could result in a significant overestimation of time-averaged exposure when using the ESM-20. Statistical techniques are available for treating censored data, therefore estimates of exposure that are more reliable can be obtained with the instrument.

There was poor agreement between the results obtained using the Nardalert XT and those obtained using the ESM-20 at a radar site. This was due to the different responses to pulsed fields of the detectors incorporated in the two instruments, and reflected the difficulties inherent in quantifying exposures at radar sites where the signals are transmitted in short pulses and the antennas rotate.

7 ACKNOWLEDGEMENTS

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