C. R. Physique 11 (2010) 541–555

Contents lists available at ScienceDirect

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Interactions between radiofrequencies signals and living organisms

Assessing personal exposures to environmental radiofrequency electromagnetic fields

Évaluation des expositions personnelles aux champs électromagnétiques ambiants

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ARTICLE INFO

Article history:
Available online 30 December 2010

Keywords:
Personal exposure assessment
Radiofrequency electromagnetic fields
Exposimeter

Mots-clés :
Évaluation des expositions personnelles
Champs électromagnétiques ambiants
Exposimètre

ABSTRACT

Recent advances in the capability of body-worn instruments for measuring the strengths of environmental radiofrequency signals have opened up a range of exciting new research possibilities. The readings from these instruments can be used in health related studies, but they have to be considered carefully when developing exposure metrics, as does the physical dosimetry concerning interactions between radio waves and the body. Several studies have distributed the instruments to large groups of people and analysed the gathered data in relation to possible determinants of exposure. This article reviews the state of the art in personal exposure measurements at radiofrequencies.

RÉSUMÉ

Les progrès récents des instruments portatifs de mesure des niveaux de champs électromagnétiques ambiants ont ouvert de nouvelles perspectives de recherches très attrayantes. Les données recueillies grâce à ces instruments peuvent être utilisées pour des études liées à la santé mais doivent être considérées avec précaution quand il s'agit d'élaborer une métrique d'exposition ; tout comme la dosimétrie physique vis-à-vis des interactions entre les ondes radio et le corps. Plusieurs études ont distribué ces instruments à de large échantillons de personnes et analysées les données recueillies pour en extraire d'éventuels déterminants de l'exposition. Cet article fait la revue de l'état de l'art dans ce domaine.

1. Introduction

Radiofrequency (RF) electromagnetic fields (EMFs) are emitted by a range of sources and are present throughout the developed environment. Spot measurements of field strength are often made in order to assess the potential exposures of people who might be present at particular locations. However, people move around over time and the RF emissions from sources may also change over time. Thus, in many situations, it is of more interest to have an instrument that can be carried on the body and which measures fields to which a person is exposed as they carry out normal work or leisure activities. Recent advances in the capability of such instruments have opened up a range of exciting new research possibilities. The instruments, known as personal exposure meters (PEMs) or exposimeters, can be carried on the body or placed nearby when a person is stationary. In this way, people's exposures can be measured and recorded over time.

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1631-0705/$ – see front matter
doi:10.1016/j.crhy.2010.11.005

Personal measurements can be used for hazard assessments, risk communication or to provide exposure information for health-related studies. With hazard assessments, the readings are compared with limit levels, e.g. the reference levels in the ICNIRP guidelines [1], and an alarm may be triggered above a certain threshold value. However, there are issues of interpretation that apply when a measurement is made close to the body, which mean a more definitive assessment is also generally required to adequately control exposures for safety purposes. These dosimetric considerations will be discussed later. In terms of risk communication, PEMs can show not only how exposures relate to some limit value, but they can also allow comparisons of relative exposure levels at different locations and from different sources transmitting in different frequency bands. This can reassure people that an unfamiliar source about which they are concerned produces exposures that are either small in relation to exposure guidelines or the exposure from more familiar sources, such as their own mobile phone. On the other hand, concern may be enhanced if the reverse is shown. Finally, the PEM measurements can be used in health-related studies, where exposure levels are correlated with some health end-point hypothesised to be influenced by RF exposure. Studies of short-term health effects, including well-being and sleep quality, in which small numbers of people are issued with PEMs over the period during which their health is studied are relatively straightforward and have already been carried out [2–5]. Another objective is to use readings from PEMs to optimise and validate predictive exposure models [6,7] so larger numbers of people can be included in studies of short term health effects. Perhaps the ultimate challenge is to extend these models so that retrospective exposure estimates can be derived in order to study long term health effects in large numbers of people.

The early studies did not fully address problems associated with much of the measured data being below the detection threshold of the PEMs. Neither did they consider the dosimetric complexities involved with combining localised and whole-body exposures. However, later studies using more sophisticated analysis of the measured data are now yielding insights into exposure levels from sources such as radio and television broadcast transmitters, base station transmitters for mobile phones, and personal use of mobile/cordless phones and Wi-Fi devices [8–11]. The data are also being examined to find out if aspects of people's lifestyle, residential location, etc., can be used as predictors of exposure and if an exposure gradient can be formulated based on these factors. This paper focuses on the measurement aspects of PEMs and the dosimetry challenges in assessing personal exposures. These include understanding how the limitations of the instruments affect their readings and interpreting the readings in terms of biologically relevant exposure metrics. The state of the art will be presented, along with suggestions for areas meriting more research and development. This is a rapidly developing field and the reader's attention is also drawn to another recent paper [12], which proposes procedures for the measurement of personal exposure to RF EMF, data collection, data management and analysis, and methods for the selection and instruction of study participants in order to harmonise protocols used in future studies.

2. Environmental RF EMFs

In order to identify the performance requirements of an RF PEM, it is important first to understand the characteristics of RF fields at the environmental locations where people spend most of their time, e.g. at home, work, school, commuting, shopping, etc. This paper will focus mainly on Europe, where the types of radiofrequency sources in the environment changed little for many years – until the early 1990s and the rapid proliferation of new consumer radio technologies beginning with the mass-uptake of mobile phones. Before this point, there were broadcast transmitters for radio and television, professional radio communication systems, e.g. for the emergency services, and industrial uses of radio power, mainly for heating. There were very few radio transmitters designed for use by the public, aside from Citizen's Band (CB), Ham (Amateur) radio systems, baby monitors and some toys. Comprehensive reviews of RF sources and exposures are available, e.g. from ICNIRP [13], and this section provides a brief summary focussing on the most important sources and technical considerations.

2.1. Transmitter frequencies and powers

Knowledge of which environmental transmitters contribute mostly to general public exposure and whose frequency bands should therefore be measured by PEMs arises from spot measurements carried out with spectrum analysers. These have revealed that, even though there are notionally sources with allocations in all parts of the radiofrequency spectrum (from 10s of kHz to 10s of GHz), most of these sources either have very low prevalence, transmit very infrequently or are used in such a way that they do not contribute significantly to the exposure of people. In fact, the radio spectrum usually presents itself as consisting of a few relatively narrow frequency ranges in which there are a great number of densely packed signals and large empty regions between them. There is a general consensus among those who have performed such measurements, but few actual publications (e.g. [14,15]) and no systematic studies examining signal strength across the full spectrum at multiple locations in a range of countries.

Short wave broadcasting has been in existence since the 1940s using frequencies in the range 2–30 MHz. However, even though it uses very high radiated powers (∼500 kW) per transmitter, there are few sites and these tend to be only in rural areas. Hence, short-wave signals have been neglected in personal dosimetry studies with the general public. VHF and UHF broadcast sites for radio and television are much more prevalent, nearer to population centres and have used the following frequencies for several decades. FM radio uses the 88–108 MHz band and UHF TV uses 470–854 MHz (Bands 4 and 5). TV transmissions continue in the 174–223 MHz range (Band 3) in some countries.

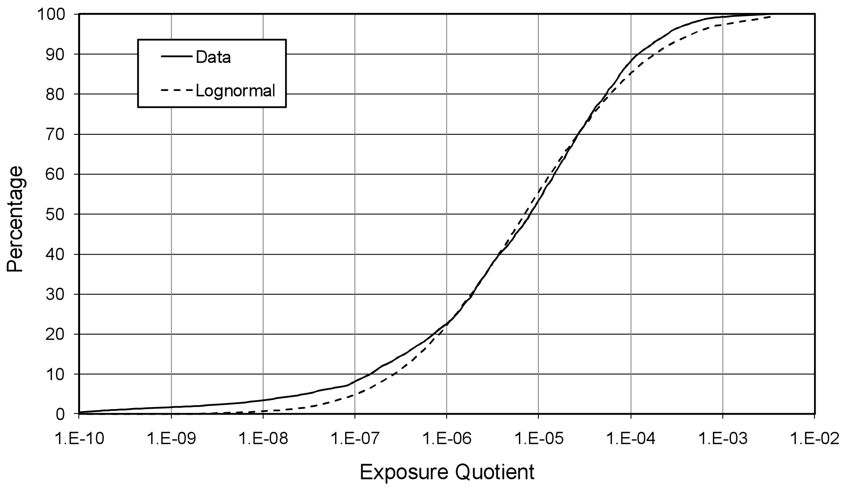

Fig. 1. Cumulative distribution of exposure quotients corresponding to 3321 spot measurements made by Ofcom at 499 sites where people were concerned about nearby base stations with a lognormal curve fitted to the data.

Of most interest to the general public and researchers are the base station transmitters used by mobile phones because there are large numbers of these within population centres in order to serve the increasing demand for network capacity. Some northern European countries had cellular systems operating in bands near 450 MHz, but these have been shut down over the past ten years. Base stations serving networks for the general public in Europe now operate in the following frequency bands: GSM900 uses 925–960 MHz, GSM1800 uses 1805–1880 MHz, UMTS (3G) uses 2110–2170 MHz. Radiated powers depend on the size of the cell covered by a base station and range from a fraction of a watt to over 100 W [15]. There are also TETRA base stations serving networks for the emergency services operating in various frequency bands, usually around 390 to 430 MHz, and radiating a few tens of watts.

The most powerful common fixed indoor transmitters are microwave ovens, with up to around 1 kW power and operating at 2.45 GHz, but these tend to operate for only a few minutes at a time and are designed to contain their power in the oven with little leakage. The base stations for DECT cordless phones transmit in the frequency range 1880–1900 MHz and have time-averaged output powers on 10 mW during calls and most emit 2 mW when calls are not being made.

Wi-Fi access points, mostly transmitting in the range 2.4–2.5 GHz but some transmitting in the range 5–6 GHz, are also present at many indoor (and outdoor) locations. The EIRP in the 2.4 GHz band is limited to 100 mW by product standards and, given that the antenna gains will be several dB, this means the radiated powers during transmission should be no more than a few tens of mW. There is some radiated power when no data are being transferred, but this is likely to be less than 1 mW (see Section 2.3).

Body-worn transmitters include mobile phones (GSM900: 880–915 MHz, GSM1800: 1710–1785 MHz, UMTS: 1920–1980 MHz), cordless phones (1880–1900 MHz) and Bluetooth headsets (2.4–2.5 GHz). Mobile phones have maximum time-averaged powers during calls of around 125 mW, except for GSM900 which has 250 mW, but these are reduced in practice by adaptive power control. The reduction is around 50% with GSM phones [16], but very much greater with 3G phones, which generally only operate at a few percent of the maximum power [17]. As with the base stations, DECT cordless phones have around 10 mW during calls. Bluetooth headsets have around 1 mW power.

2.2. Spot measurements of power densities

There have been a great many spot measurements carried out of exposure levels near to mobile phone base stations. Generally, these take into account exposure contributions from all of the signals in the bands used by base stations at the time of the measurement, but ignore other parts of the spectrum such as that used by broadcast transmitters. An example of such a measurement programme is the Audit of base stations that has been carried in the UK by Ofcom since 2001 [18]. Initially the Audit focused on schools, then hospitals and it now covers a range of sites where people request measurements through the Ofcom website. The locations are generally accessible to the public, some indoor and some outdoor, and measurements are not normally made in private homes.

The data on the Ofcom website for site visits up to the end of 2007 were downloaded. 541 sites had been visited up to this point at which a total of 3321 measurements had been made. The sites comprised 339 schools, 37 hospitals and 165 other locations. Ofcom calculated total exposure quotients from its measured data and Fig. 1 shows the cumulative distribution of these values. The quotients are in relation to the ICNIRP general public reference level [1] and they were calculated by dividing the power density of each individual measured signal by the reference level at its frequency and then summing these individual signal quotients to obtain a total quotient of the reference level, as in [14].

Table 1
Summary of exposure quotients measured during the Ofcom Audit up to the end of 2007, and equivalent power densities and electric field strengths assuming a reference level of 4.5 $\mathrm{W\,m^{-2}}$. Median values are given followed by the range from 5th to 95th percentiles in brackets.

Category	Number of measurements	Exposure quotient, $\times 10^{-6}$	Power density, $\mathrm{\mu W\,m^{-2}}$	Electric field strength, $\mathrm{mV\,m^{-1}}$
All data	3321	8.1 (0.03–250)	37 (0.13–1100)	120 (7.1–650)
Outdoor	1809	17 (0.052–314)	77 (0.23–1400)	170 (9.3–730)
Indoor	1516	2.8 (0.024–124)	13 (0.11–560)	69 (6.4–460)

Fig. 1 includes a lognormal curve fitted optimally (least squares) to the data. This suggests the data are approximately lognormally distributed, although with a longer tail towards the lower quotient values. The quotient values are 8.1×10^{-6} (3.0×10^{-8}–2.5×10^{-4}), where the first figure is the median value and the values in brackets are the range in the data from 5th to 95th percentile. Around 55% of the measurements were made outdoors and these had higher exposure quotients than the indoor measurements. The median quotients for the outdoor and indoor measurements were 1.7×10^{-5} and 2.8×10^{-6} respectively, i.e. the outdoor median was around six times higher. The geometric mean exposure quotient across all the data was 5.6×10^{-5}.

In order to consider the implications of these measurements for personal dosimetry, it is necessary to convert the values to electric field strengths, the quantity that is measured. The reference level varies from 2 to 10 $\mathrm{W\,m^{-2}}$ over the frequency range considered in the measurements (TETRA at 390 MHz to UMTS at 2170 MHz). Hence, the precise power density corresponding to the exposure quotient cannot be evaluated based solely on the total exposure quotient. However, the variation of the reference level is very much less than the variation in the exposure quotients in Fig. 1 so approximate power density levels can be calculated based on an assumed value. Taking a value of 4.5 $\mathrm{W\,m^{-2}}$ (the value at 900 MHz) for the reference level indicates the power density and equivalent electric field strength values shown in Table 1. The (arithmetic) mean power density was 0.25 $\mathrm{mW\,m^{-2}}$.

The data in Table 1 indicate electric field strengths that range from around 10 $\mathrm{mV\,m^{-1}}$ to a few hundred $\mathrm{mV\,m^{-1}}$ indoors, where people spend most of their time. However, in considering these data it is important to recognise that the sites were selected according to people's concern about a nearby base station and so these field strengths may be higher than would be found at locations representative of general population exposures.

Many countries have carried out measurement programmes similar to the UK Audit of base station emissions, for example ANFR is conducting a programme in France. However, there are far fewer spot measurements relating to exposure of the general population to signals from broadcast transmitters. The radiated power of VHF and UHF broadcast transmitters can be much higher than from base stations (10s of kilowatts against up to around 100 W), but there are fewer of them and the highest power broadcast transmitters have radiating antennas mounted on very tall masts, typically over a 100 m in height. Also, the beams from broadcast transmitters are directed towards the horizon so field strengths at ground level are small.

Radio and television broadcast signal field strengths were measured at 300 randomly chosen locations in an area around Munich and Nuremberg (Germany) [19]. The interest of the study was in whether the levels had changed as a result of switch-over from analogue to digital broadcasting, and the measurements were made before and after this occurred at each location. The data provide an indication of typical environmental field strengths from broadcast transmitters, although it is a small dataset relating to only two transmitters and the measurements were all made outdoors. The median power density was 0.3 $\mathrm{\mu W\,m^{-2}}$ (11 $\mathrm{mV\,m^{-1}}$) for the analogue signals and 1.9 $\mathrm{\mu W\,m^{-2}}$ (27 $\mathrm{mV\,m^{-1}}$) for the digital signals, both appreciably less than the 77 $\mathrm{\mu W\,m^{-2}}$ found in Table 2 with base station signals outdoors. This is not too surprising because TVs usually use fixed directional (yagi) antennas mounted on top of buildings to receive signals and so they can operate with lower environmental field strengths than cellular phones, which do not have directional antennas. FM radio signals had median power densities of 0.3 $\mathrm{\mu W\,m^{-2}}$ (11 $\mathrm{mV\,m^{-1}}$), similar to the TV signals and the values ranged over approximately two decades either side of the medians for all types of broadcast signal.

2.3. Waveforms and modulation

When considering how to categorise exposures of people, it is important to consistently account for the signal characteristics of particular communication systems when summing them together in the context of a chosen exposure metric. This involves considering whether the waveform is continuous or intermittent and whether the way information is carried affects important aspects of the signal [20].

VHF broadcast radio signals are essentially continuous and have the audio information encoded into slight changes in the frequency of the signal. Analogue TV signals are also continuous, but have two narrow subcarriers evident that are 6 MHz apart in 8 MHz wide channels. For example, UK channel 21 in the UHF band (470 to 478 MHz) has the video carrier centred at 471.25 MHz and the audio carrier centred at 477.25 MHz. The power level of the video carrier is twice that of the audio carrier and both carriers have amplitude and phase variations according to the information carried. There are $\sim$5 μs frame synch pulses in the transmission of the video carrier 50 times every second and these introduce a 50 Hz power modulation. Digital TV signals are far more complicated in structure than analogue ones and do not show separate subcarriers (these are present but their spectra overlap) or appreciable power modulation.

Table 2
Characteristics of typical pulse modulated RF signals in the environment.

System	Scenario	Duration, ms		Duty factor,	Burst rate,
		Burst	Frame	%	Hz
GSM	Handset, talk	0.58	4.6	12	217
DECT	Base, standby	0.08	10	0.8	100
DECT	Handset, talk	0.4	10	4	100
Wi-Fi	Router, standby	1	100	1	10

Several types of environmental radio signals use Time Division Multiple Access (TDMA) in which several radio transmitters at different locations take it in turns to transmit on a given frequency channel. This results in the signals from any given transmitter being "pulse modulated" [21]. Examples of systems where this occurs and typical emission scenarios are shown in Table 2.

With a pulse modulated signal the time-averaged power is lower than the peak power (power during transmission) by a quantity known as the duty factor. For example, a DECT base station on standby (when not making a call) produces 100 "beacon" bursts, each of 80 μs duration and at a power level of 250 mW, every second. It therefore transmits for 0.8% of the time on average and has an average power level of 2 mW.

The duty factor of Wi-Fi equipment is variable and depends on many things. However, time sharing when multiple terminals are using the same access point (or router) would limit the extent to which any one device can monopolise the system. A beacon pulse is emitted every 100 ms from access points even when no data are being transferred. Schmid et al. [22] found these pulses were of 2.5 ms duration, while Foster [23] has found pulses of a few tens of microseconds. The author of this paper has found pulses of around 1 ms duration (unpublished data) and so it seems the baseline duty factor of Wi-Fi access points is dependent on the make/model. Taken together with the power of a few tens of mW during transmission (see Section 2.1), a baseline radiated power of around 1 mW or less seems likely for Wi-Fi access points.

2.4. Signal fading and multipath propagation

Fading is a fundamental characteristic of radio signals in the environment, particularly at the relatively high frequencies of interest for PEM measurements. Radio signals are reflected from buildings and other structures, leading to multiple paths for a signal to follow from the transmitter to the receiver. The signal contributions arriving via these different paths travel different distances and so arrive at slightly different times. Also, the path lengths differ by amounts that are larger than the wavelength (typically ∼10 cm), meaning that the signal contributions can sum together to reinforce or cancel-out at a given position. The consequence of multipath propagations is large field strength variations over distances of the order of the wavelength and also over short time intervals (fractions of a second). Fading will not be discussed in detail here, but it is an important consideration in making and interpreting PEM measurements. Various statistical models have been developed and are covered in text books and Larchêveque et al. [24] have evaluated their implications for RF exposure assessment.

3. Personal measurement instruments

The fundamental practical requirements of any PEM are that it should be small, lightweight and have a long battery life. It should be robust against impact, vibration, tampering, water splashes/humidity and variations in temperature. It should be discreet so as not to attract attention when carried and it should be easily worn or placed near the body. Achieving these basic practical requirements necessitates compromises in the measurement performance of the PEM. This section summarises how measurement instruments for personal exposures have developed over time. It identifies the key performance characteristics, practical compromises in design, and evaluations that have already been performed. Understanding the meaning of the reading from a PEM and treating it appropriately is critical to developing exposure metrics.

3.1. Power frequency PEMs

Personal dosimetry with body-worn instruments is a mature area of research at power frequencies (50/60 Hz) and many epidemiological studies have been carried out using instruments such as the EMDEX (see Fig. 2a) to measure magnetic field strengths. This PEM has dimensions 17 × 7 × 4 cm, weights 340 g and can be easily strapped to the waist. Expectations of researchers using PEMs for radiofrequency studies are that they will perform adequately and be similarly easy to use, but the design challenges with RF instruments are much greater as will be explained below.

Traceability of measurements to standards so they have a defined uncertainty is an essential requirement for any measurement protocol. Power frequency PEMs are easily calibrated using Helmholtz coils, a relatively inexpensive desk-top item of equipment, fed by a calibrated current source. In between regular formal calibrations, the instruments can be tested by the field workers using a check source (Fig. 2b), e.g. before and after deployment to each study subject so any failures can be quickly identified. In principle, it would be ideal if similarly simple instrumentation and quality control methods could be used at radiofrequencies. However, in practice more extensive facilities and bulky fixtures such as GTEM cells are required

Fig. 2. EMDEX personal exposure meter, as used in many epidemiological studies at 50 Hz, and a check source in which it can be inserted to verify correct function before issue during a study.

for calibrations [25] and check sources are not yet readily available. It is important to use realistic signals for calibration (not sinusoidal ones) since PEMs may respond differently to modulated signals.

Power frequency measurements are essentially narrowband, with the spectral power of the signal to be measured close to either 50 or 60 Hz, depending on the country, and its first few harmonics. At any given location, there are many radiofrequency signals present in the environment, operating over a very wide range of frequencies and with a wide range of waveforms and signal strengths. In principle, the frequencies can range from tens of kHz to tens of GHz, but as explained above, the signals that tend to dominate exposures at locations where the general population spends most of their time operate in a somewhat narrower frequency range, from 80 MHz to a few GHz. Even so, to design a portable instrument remains a considerable challenge.

3.2. Broadband RF PEMs

The earliest forms of RF PEMs were designed for use in occupational environments, such as working on towers with high power broadcast antennas, where there is a possibility that exposure guidelines might be approached. Example instruments are the Narda Radman and Nardalert XT, which have been available since the mid 1990s (Fig. 3). Workers wear these clipped to their body, perhaps in a chest pocket, and the instruments give an audible warning when the field strength exceeds a pre-set level, indicating that the worker should retreat. Initially, the PEMs lacked a data logging facility, but current designs can store electric field data to memory so a trace can be downloaded at the end of a shift.

These RF PEMs measure across a wide range of frequencies, ∼1 MHz to 10 s of GHz, but they do not discriminate individual signals and simply give a measurement of the total root mean square (rms) field strength in their entire measurement bandwidth. This broadband operation means they accumulate RF noise from across their entire measurement bandwidth, which makes them very insensitive. Typically, the background noise level is a few $\mathrm{V\,m^{-1}}$, significantly higher than typical RF electric field strengths at locations where the general population spend most of their time, which are generally less than $1\ \mathrm{V\,m^{-1}}$ (see Section 2.2). Nevertheless, these instruments have been used successfully within a feasibility study that attempted to characterise the exposures of a cohort of RF-exposed workers in the broadcast and telecommunications industries [26]. Useful results were obtained, but readings above the noise floor could only be obtained when workers were near antennas at high power broadcast sites.

3.3. Narrowband RF PEMs

The key to improving the sensitivity of RF PEMs is recognition that the sources of interest only operate in certain narrow frequency ranges. Measuring only in these bands allows the exclusion of noise in other parts of the spectrum, but requires highly selective filters tuned to the bands of interest. The latest generation of narrowband RF PEMs has been designed to perform measurements in this way.

Two manufacturers produced narrowband RF PEMs around 2004/5, but these instruments differed somewhat in their technical specifications and in the way that they were designed to be used. Satimo (http://www.satimo.com), previously Antennessa, developed the PEM shown in Fig. 4a, which is designed to be mounted anywhere on the body (but facing away from it) or placed on a surface, e.g. item of furniture, near to the body. The other PEM (Fig. 4b) was developed by Maschek (http://www.maschek.de). It is smaller than the Satimo PEM and designed to be strapped to the upper arm and worn under the clothes. Both PEMs have been improved by their manufacturers over time to make them more sensitive and able to measure signals within more frequency bands. This makes any published comparison or evaluation of the instruments only valid for the versions actually tested and liable to become historical rather rapidly.

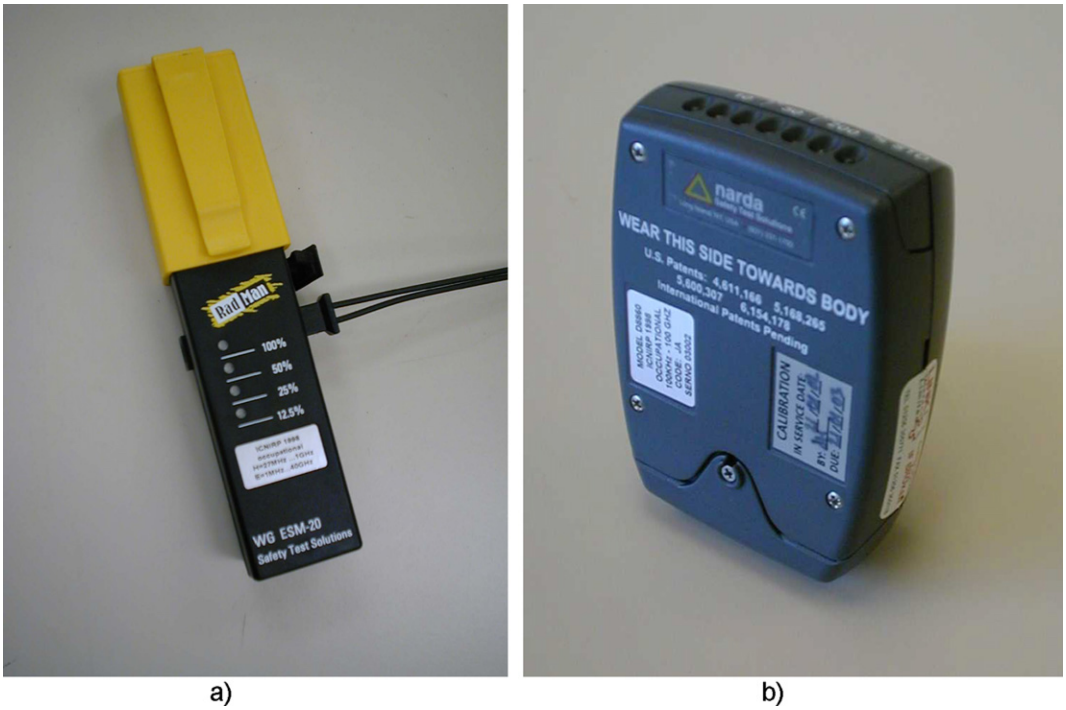

Fig. 3. Broadband PEMs designed for warning of exposure hazards in occupational situations.

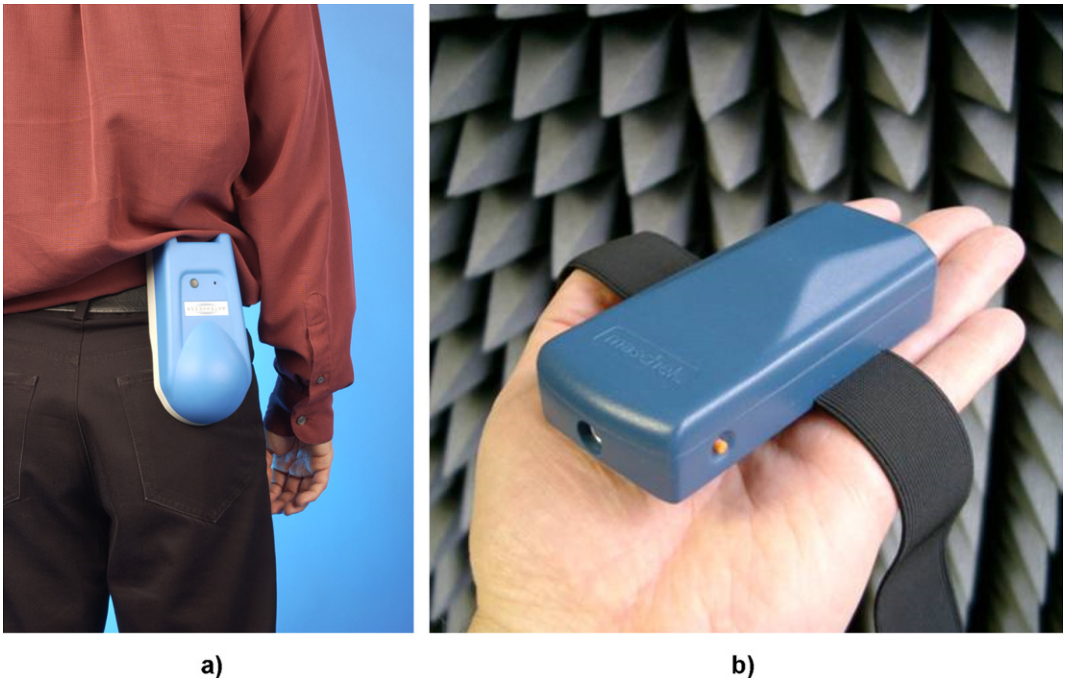

Fig. 4. Antennessa (now Satimo) DSP090 (a) and Maschek ESM-140 (b) PEMs. (*Photo of ESM-140 courtesy of Prof. K. Radon, Ludwig Maximilian University, Munich.*)

Detailed laboratory measurements and a small volunteer trial were performed to evaluate an early stage model of the Satimo PEM, the DSP090 [27]. This was able to measure electric field strengths in nine separate frequency bands and had a detection threshold of 50 $\mathrm{mV\,m^{-1}}$. The PEM was found to have a performance broadly in line with its intended purpose and the results of the study enabled the manufacturer to further develop the instrument. However, the difficulties with filter

Table 3
Frequency bands specified for PEM measurements and their availability with current instruments.

Frequency band		Maschek ESM-140	Satimo EME Spy121
Environmental sources	MHz		
VHF FM broadcast radio	88–108		✓
Band 3 television	174–223		✓
TETRA (bases and phones)	380–400		✓
Band 4/5 television	470–830		✓
GSM900 mobile phones	880–915	✓	✓
GSM900 base stations	925–960	✓	✓
GSM1800 mobile phones	1710–1785	✓	✓
GSM1800 base stations	1805–1880	✓	✓
DECT cordless phones	1880–1900	✓	✓
3G (UMTS) mobile phones	1920–1980	✓	✓
3G (UMTS) base stations	2110–2170	✓	✓
Wi-Fi (wireless networks)	2400–2500	✓	✓

design were evident, with some breakthrough of out of band signals occurring in the measured bands. This is likely to be common to all narrowband PEMs as the filter specifications are exacting.

The directional receiving characteristics of both narrowband PEMs were investigated when exposed to a plane wave and not mounted on the body [28]. The Satimo PEM contained three orthogonal receiving antennas, while the Maschek PEM contained a single dipole. The consequences of this were evident in that the Maschek PEM had a less isotropic response than the Satimo PEM. However, the readings from the Satimo and Maschek PEMs have been compared when they were both worn by the same subjects at the same time and moderate agreement was found [29]. There are two possible reasons why the less isotropic response of the Maschek may not be a problem in practice and the space saved by having only one antenna in the instrument is clearly an advantage. Firstly, radio signals at telecommunications frequencies exhibit fast fading, with the field strength and polarisation varying rapidly over time (see Section 2.4). When many measurements are averaged over long periods of time, as usually happens when PEM data are analysed in studies, this will tend to average-out the directional characteristics. Secondly, the Maschek PEM is designed to measure only the radial field component at the surface of the arm, which should be the dominant component because the arm is conductive and the electric field parallel to its surface should be small. Having only a single antenna may be more of a problem for the Maschek PEM when it is taken off the body and placed nearby, e.g. at night, because the dominant field component may not be parallel to its sensor.

The specifications of both PEMs have developed since the above publications and the latest versions do not seem to have been independently evaluated or compared in the literature. The more recent versions of the instruments are specified to measure over the frequency bands in Table 3. The specified detection thresholds of the PEMs are 50 $\text{mV}\,\text{m}^{-1}$ and 10 $\text{mV}\,\text{m}^{-1}$ for the Satimo and Maschek PEMs respectively, although Satimo plans to have a 10 $\text{mV}\,\text{m}^{-1}$ detection threshold in the next version of its PEM.

Both PEMs use a combination of filters and amplifiers to separate the frequency bands in which the measurements are to be performed, and the filter performance requirements are quite stringent because some bands are close together – or even adjacent in the case of GSM1800 base stations and DECT. In practice, compromises have to be made and the filter characteristics are imperfect, leading to some breakthrough of signals from one band into another and a response that varies somewhat within each band.

In order to conserve battery life, the PEMs shut down their circuits while measurements are not being made and “wake-up” once every few seconds to make a measurement quickly in all bands. Some of the signals to be measured are pulse modulated, e.g. Wi-Fi and DECT and so there would be a possibility of making a measurement in the gap between bursts and not registering the signals. Hence, the PEMs sample very rapidly for a short period while making a measurement in these bands and then examine which samples have detected a burst and which have not in order to verify the signal type is appropriate to the band in which it has been found and further improve selectivity.

It is essential to realise that the reading from the PEMs relates to the burst power with TDMA signals and not the average power. For example, with a Wi-Fi signal having 1% duty factor (see Table 2), the rms electric field strength will be ten times lower than that indicated by the PEM (1% of the power) and this has to be considered in developing exposure metrics. Also, the PEM will give exactly the same reading with the Wi-Fi signal, irrespective of the duty factor, which may increase with traffic loading.

4. Dosimetry considerations

Researchers have so far tended to use the electric field strength reading (total of all bands) from the PEM directly as an index of exposure; however, a biologically relevant exposure metric has to take into account the spatial and temporal distributions of electric (and/or magnetic) field strength inside the body tissues. This information has (ideally) to be reduced to a single number (the index of exposure) in a way that takes account of the health condition being investigated. An example of such an approach is where in the Interphone study absorption of RF energy from mobile phones at the location of brain tumour initiation is being developed as an index of exposure [30]. For health conditions that are more systemic and

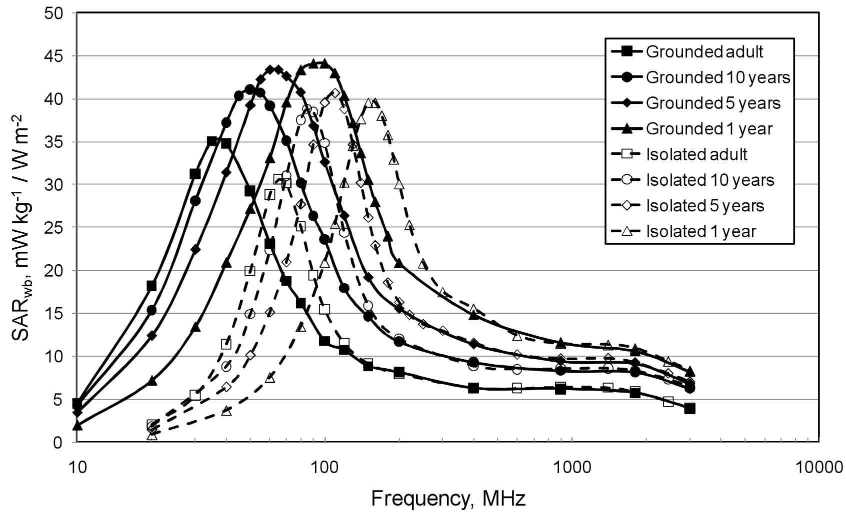

Fig. 5. Variation of the whole-body SAR produced per unit power density as a function of frequency in the adult male phantom NORMAN, and child phantoms of three different ages grounded and isolated.

not so localisable to a particular tissue/organ/region of the body, it is less obvious how to account for the spatial distribution of fields inside the body in developing an index of exposure. However, the choice of a physically meaningful quantity such as cumulative RF energy absorption in the body does provide a rationale for combining exposure contributions at multiple frequencies and for summing exposure over time. Additionally, data can be partitioned in a way that accounts separately for contributions from different types of signals, e.g. continuous vs pulse modulated.

4.1. Exposure to plane waves

For a given exposure scenario, computer modelling can be carried out to relate the field strength outside the body to the spatial distribution of field strength within the body, and hence whole-body or localised SAR. However, the body posture changes over time and the field distribution incident on the body is also dynamic. In reality, the exposure arises from multiple plane waves incident simultaneously from different directions (see Section 2.4) and also non-plane wave contributions arising from scatterers in close proximity to the body. Computational scenarios where the body is exposed to a single plane wave, usually with vertical polarisation and incident from the front of the body bear little relation to reality, but do allow certain insights to the fundamental processes of RF energy absorption and the factors affecting it.

Classical RF absorption curves relating whole-body specific energy absorption rate (SAR) to a vertically polarised plane electromagnetic wave incident on the front of a person standing with their arms by their side are shown in Fig. 5 [31,32]. The figure shows calculation results for the NORMAN adult male voxel phantom at full size and scaled to represent children of three different ages both connected to and isolated from a conducting ground plane beneath their feet. Many different adult and child phantoms are now available to researchers and the results in this section are typical of those that can be found. However, the precise data vary with individual phantom size and anatomy, as shown by Conil et al. [33].

Fig. 5 shows a strong variation in whole-body SAR with frequency and a pronounced resonance where the maximum SAR occurs. The frequency of the resonance depends on the body size and grounding conditions and lies approximately between 30 and 200 MHz. Signals from VHF broadcast transmitters therefore lie within the resonance range, but signals from other environmental transmitters of interest in personal RF exposure measurements operate around 400 MHz and above, and therefore beyond the resonance range. At these frequencies whether the body is in electrical contact or isolated from the ground has little effect on SAR, but body size is an important factor. It is evident that children have higher SARs than adults, i.e. they absorb more energy per unit body mass, at frequencies above the body resonance. Above 400 MHz, a 10 year old child has around 30% higher SAR than an adult and a 1 year old child has around twice the adult SAR.

Between 400 MHz and 2 GHz, where most transmitters of interest operate, the SAR is fairly constant as a function of frequency, especially in adults. SAR then reduces at frequencies above 2 GHz. This is because the penetration of radio waves into the body tissues becomes less with rising frequency and absorption of energy becomes mainly in the superficial tissues of the side of the body facing the incident wave, i.e. the absorption takes place is in an increasingly small proportion of the body's mass. An important quantity that describes the penetration of radio waves into body tissues is known as the skin depth and this represents the distance into a given tissue that a radio wave travels before its electric field strength is reduced to 1/e (around 37%) of its initial value. Given that SAR is related to E^2, this implies a reduction in SAR to 13% of its initial value over a distance equal to the skin depth. Example skin depths are shown in Table 4 for muscle and fat (not infiltrated) [34]. This shows how the absorption of the radio waves becomes confined to the surface of the body as frequency increases and how this effect is most pronounced in the highest conductivity tissues.

Table 4
Example skin depths for penetration of radio waves into muscle and fat tissues at typical telecommunications frequencies measured by PEMs.

Frequency, MHz	Muscle		Fat	
	Conductivity, $S\,m^{-1}$	Skin depth, mm	Conductivity, $S\,m^{-1}$	Skin depth, mm
400	0.80	28	0.041	124
900	0.94	17	0.051	74
1800	1.34	10	0.078	42
2450	1.74	7.7	0.105	31
5200	4.27	3.3	0.255	14

Changes in the whole-body SAR characteristic in relation to changes in body posture have been investigated. In addition to the basic stood with the arms by the side posture, situations have been considered with the arms held above the head, with the arms held out sideways and with the body in a sitting posture [35]. While people are likely to spend relatively little of the day in the first two additional postures, they are likely to spend a large part of the day sitting and this should be taken into account. People also spend a large part of the day lying down in bed, which could involve a range of postures. For exposure assessment purposes, it is necessary to define an "average" absorption characteristic that takes into account the range of postures that people adopt over time with appropriate weighting factors. It is also necessary to account separately for the exposure of children, which is higher than adults.

4.2. Field strength near the body

The above discussions relate to the relationship between whole-body SAR and plane electromagnetic waves incident on the body. When a PEM is worn on the body, it measures the sum of the incident field and the field scattered by the body as a result of reflection and current flow in the body tissues. Moreover, the skin-depth related effects mentioned above mean that the body effectively casts a shadow over a PEM placed on one side of it from a wave incident on the other side. The shadowing effect has been investigated computationally and experimentally in the FM and GSM900 bands and found to be up to 30 dB [36]. For the GSM900 frequency, where the wavelength is small in relation to the body height, reflection from the surface of the body on which the wave was incident gave rise to a pattern of rising and falling field strength with increasing distance away from the body, and the distance between successive maxima (or minima) was equal to half a wavelength (16 cm). The surface of the body was at a field strength minimum because of its high conductivity and this means that measurements with PEMs within a few cm of the body surface are quite sensitive to the distance from the body.

Bahillo et al. [37] extended the above work on shading with a single plane wave to calculate the average field strength reduction at the location of a body-worn PEM when a plane wave is incident from several different directions, each for a different proportion of the time. This showed that shading reduces the PEM reading by much less than 30 dB on average in a dynamic scenario, where the exposure is changing due to movement of a person or multipath propagation (see Section 2.4).

Iskra et al. [38] have considered variations in the relationship between incident field strength and total field strength within 10–50 mm of the body at 900 MHz as an aspect of measurement uncertainty. They carried out simulations of plane waves incident from various directions and with various polarisations: a total of 56 simulations. The fields at 30 randomly chosen locations in front of the torso at each of 10 and 50 mm distance were evaluated for each simulation. The variations were much less at 50 mm distance than at 10 mm distance. Generally, the field strength close to the body was several dB less than the incident field strength. For example, in the "random urban" scenario with adults, the mean ratio and standard deviation were -6.21 ± 1.80 dB at 10 mm distance, reducing to -4.25 ± 0.77 dB at 50 mm distance. The use of a second PEM giving an additional reading on the opposite side of the body and then averaging the two readings was found to further reduce the variations to -3.64 ± 0.85 dB at 10 mm distance and -1.74 ± 0.33 dB at 50 mm distance. Whether wearing two PEMs would be practical in an actual study is open to question, but nonetheless this is an interesting result. A limitation of this analysis is that it only considers one plane wave incident at a time. As such, it does not account for the interference between the fields of different plane waves as they pass through a common point. Waves passing through a point can either add or subtract from each other in terms of field strength according to their relative phases and this leads to a complicated field distribution close to and inside the body.

4.3. Multiple plane waves

As explained in Section 2.4, realistic exposures involve multiple wave contributions incident on the body simultaneously from different directions and with varying polarisations. In principle, one could generate a large number of plane wave solutions and then sum these together with appropriate statistically derived weighting functions to generate a more realistic generic solution relating SAR to the field strength at a point near the surface of the body where a PEM might be placed. Vermeeren et al. [39] have developed a fast approach based on combining thousands of plane wave calculations of whole-body SAR in an ellipsoidal model of the body. They have then used this approach with actual PEM measurements to categorise exposures in 28 different micro-environments [11] in terms of the whole-body SAR produced. The main limitation of this approach is its use of a simple model of the body without anatomical features. Further work would be necessary to consider exposures in particular organs/parts of the body.

Neubauer et al. [40] have used ray tracing software to model a representative urban scenario with street corridors and buildings, one of which has a transmitting antenna mounted on it for frequencies of 100, 946 and 2140 MHz. They also developed an indoor model of a coffee shop scenario for simulations at 2450 MHz. For several locations in the models where a person could be present, they decomposed the incident field distribution into a set of plane waves of given field strength, delay and incidence angle. A second modelling exercise was then carried out with a human body model exposed to the combination of plane waves and the field strength was evaluated at locations on the body surface where a PEM might be worn. The results showed the difference between the field strength at the PEM location and the average field strength over the volume occupied by the body without the body present. A general trend for the field at the PEM to be lower than that averaged over the body volume was found, although a large variation between worst case underestimation and overestimation was found. Reduction factors for 946, 2140 and 2450 MHz were 0.76, 0.87 and 0.64 respectively, while no reduction was found at 100 MHz (factor = 1.0). Neubauer et al. note that other studies have found greater reduction factors and state that their study does not allow final conclusions about reduction factors to be drawn.

4.4. Sources near the body

An important issue to consider in developing exposure metrics is how to combine plane wave exposure contributions from distant sources with non-uniform exposure arising from sources used in close proximity to the body such as mobile/cordless phones and Wi-Fi laptops. However, while it is tempting to consider that plane wave sources produce a relatively uniform exposure throughout the body, as explained in Section 4.1, this is not the case because of factors such as the skin depth. Thus, combining plane wave exposure contributions at different frequencies requires a similar treatment to combining plane wave and localised exposures, where the interest is in particular tissues.

Sources close to the body produce radio waves that spread out around them and so the field strength reduces rapidly with increasing distance from the source. For this reason, the parts of the body closest to such sources are more exposed than other regions of the body. The closer a source is used to the body and the smaller it is, the more localised is the exposure that results.

Provided a tissue region of interest can be defined, such as the brain, it is possible to carry out simulations to identify the SAR produced by plane and non-plane wave exposure scenarios in these regions and then to combine the two. Methods similar to those described above can then be used to extend the analysis to consider the possibility that the plane waves incident on the body have a statistical distribution in terms of their number, strength, direction of incidence and polarisation.

The field strength read out by a PEM when a transmitter is close to the body is difficult to relate to exposure because it is related to the distance of the PEM sensor from the transmitter, rather than the distance from the transmitter to the body. Given this, the best approach is to simply interpret the PEM reading as showing when a body-worn transmitter is active and then to calculate the SAR based on the location of the transmitter and its known emission characteristics (frequency, power, waveform).

5. Measurement experience and approaches

Several studies have so far evaluated exposure using PEMs in sample groups of volunteers [2–11]. These studies have analysed their data in terms of the readings gathered in particular measurement frequency bands, personal characteristics of the volunteers and where the measurements were made. Knowledge of the latter has been gained through the use of diaries kept by the volunteers supplemented, in some cases, by the use of GPS devices carried by volunteers. This section briefly summarises the results from these studies, highlighting lessons learned and methods developed.

5.1. Sensitivity aspects

The measurement data gathered with PEMs have proved to be highly variable, as with the spot measurement data of Section 2.2, and a substantial proportion of the data have been below the 50 $\mathrm{mV\,m^{-1}}$ detection limit of the PEMs. Röösli et al. [41] have developed a method for estimating the mean field strength based on an assumption of lognormality in the distribution of the data. This regression on order statistics (ROS) method seems to produce plausible estimates of the mean field exposure even when only a few values are above the detection threshold. Further studies would be helpful to derive uncertainty estimates and identify any limitations to the accuracy of this method that might become apparent with ill-conditioned data. For example, the reading from the PEMs is quantised to 10 $\mathrm{mV\,m^{-1}}$ steps, which may have implications under certain conditions.

5.2. Population measurements

In general, the studies performed so far have taken the readings from the PEMs at face value and not considered implications about how the PEMs respond to the under-lying signal aspects. Hence, a degree of caution is necessary in interpreting any trends in relative exposure contributions identified in studies. In particular, any influence of DECT, Wi-Fi and GSM handset signals on mean exposures may have been over-estimated because these signals are of a TDMA nature with low duty factors. Also, signals that are only intermittently present, including those from GSM base stations that do not carry the broadcast channel, will be neglected if they are not present when the PEM takes its measurement sample.

A German group has carried out several studies using Maschek PEMs to evaluate health effects in relation to exposures [2–4]. The first study was of well-being in 329 adults, the next was of well-being in 1498 children and 1524 adolescents, and the third study was of behavioural problems in the group of children and adolescents. The PEMs were used for a 24 hour period during which E-field was measured in the eight bands shown in Table 3 once every second, i.e. 86,400 samples. Many of the measurements were below the 0.05 $\mathrm{V\,m^{-1}}$ detection threshold and these were replaced by an E-field value equal to half the detection threshold, i.e. 0.025 $\mathrm{V\,m^{-1}}$, in determining the root mean square (RMS) E-field in each band. The RMS fields in the bands were then normalised to the ICNIRP reference level [1] at the appropriate frequency and summed together (on a squared basis) in order to produce exposure quotients. While an exposure gradient (quartiles) was produced within the populations, the substitution method adopted with the samples below the detection limit does limit the conclusions that can be drawn regarding average exposure levels. Also, the summing together of fields from localised exposures in the mobile phone bands with those associated with whole-body exposures in the other bands does not account for the different dosimetric considerations.

Another German group has used the Satimo PEM to evaluate exposures in a large population sample [5]. The participants did not carry the PEMs and spot measurements were made with the PEMs at four locations on their beds instead. 70 measurements were made at each location over a 5 minute period, leading to 280 measurements in total. The study was principally interested in base station downlink bands and the results from the three such bands were summed together on a root sum square basis to determine the mean total electric field strength for each participant. Measurements were successfully completed for 1326 participants and for 68% of these the exposure was below the 0.05 $\mathrm{V\,m^{-1}}$ detection threshold. The data were dichotomised so those with mean fields above 0.1 $\mathrm{V\,m^{-1}}$ were regarded as exposed and those with fields below this level were regarded as unexposed. Again, the inferences that can be drawn about average exposures are limited because of the way the data were processed. No account was taken of exposure away from the bedroom, e.g. while at work, or use of mobile phones.

A Swiss group initially carried out studies to refine a predictive model for exposures using spot measurements with a frequency-selective probe [6] and then using measurements with the Satimo PEM [7]. Week-long PEM measurements were made with 166 volunteers [8] at Basel and these volunteers also kept an activity diary. The method of Röösli [41] was used to treat measurements below the detection threshold. The mean weekly total (across 12 measured bands) exposure was 0.13 $\mathrm{mW\,m^{-2}}$ across all volunteers and the range was from 0.014–0.881 $\mathrm{mW\,m^{-2}}$ for individual volunteers. Overall, 32% of the exposure came from base stations, 29% from handsets and 23% from DECT. The highest mean values were found when in trains, trams, airports and buses. It was also noted that exposures were higher during the day than at night.

Viel et al. [9,10] carried out a study where 377 volunteers used Satimo PEMs for 24 hours in the cities of Lyon and Besancon in France. Accounting for measurements below the detection threshold, the mean total exposure was 0.11 $\mathrm{mW\,m^{-2}}$ (0.201 $\mathrm{V\,m^{-1}}$), very similar to that found by the Swiss group [8], and use of transportation was also found to be a factor in higher exposures, particularly for mobile phone handset contributions. Exposures were higher for people residing in urban locations than in rural ones, with peri-urban locations giving intermediate exposures.

It is interesting to compare the mean exposures found in the Swiss and French studies with the mean exposure in the spot measurements from the UK's Audit of mobile phone base stations (Section 2.2). The Audit shows a mean power density of 0.25 $\mathrm{mW\,m^{-2}}$, around two times higher than these measurements, which include other sources besides base stations. This probably reflects that the locations chosen in the Audit had somewhat higher exposures than would reflect general population exposures. This is to be expected, given the criteria for their selection.

5.3. Micro-environmental measurements

While the French population studies above categorised exposures by micro-environment according to diaries kept by the volunteers, Joseph et al. [11] focused primarily on exposure in 28 different micro-environments rather than on a randomly chosen set of users. However, at least 5 hours of measurements were taken in each micro-environment, with samples every 10 s. The values of field strength given in the paper are 95th percentiles and so cannot be easily compared with the results of the above studies. The paper finds indoor measurements can be higher than outdoor ones (based on 95th percentiles) because of the presence of Wi-Fi and DECT. However, because these use TDMA signals, this conclusion should be treated with caution (see Section 5.2). Similar results to the above studies were found in public transport environments, where the influence of mobile phone handset transmissions caused relatively high exposures.

Finally, there is an ongoing study in the Netherlands [42] which aims to use personal exposure measurements with the Satimo PEM to analyse exposures during around 30 everyday activities in order to produce an activity exposure matrix.

There is clearly a need to ensure comparability of the data gathered in studies of the type described above and for standardised approaches so that data sets from different studies can be pooled. A recent paper by Röösli et al. seeks to ensure this occurs by setting out a standardised protocol for such measurements [12].

6. Summary and conclusions

A great deal of work has been performed over the past few years to develop and evaluate a new generation of body-worn measurement instruments for use in studies of exposure of the general population to environmental radiofrequency (RF) electromagnetic fields (EMFs). These personal exposure meters (PEMs) can now be regarded as sufficiently robust and reliable for use in studies of exposure trends and people's health, and the first publications on these topics are now available. However, care is required in interpreting the readings from the PEMs and these have to be treated appropriately when developing exposure metrics in studies. In particular, the PEMs respond to the peak power of pulse modulated (TDMA) signals and failure to account for this will lead to over-emphasis of DECT, Wi-Fi and GSM handset contributions to time-averaged exposure.

The electric field strength of RF signals in the environment is generally small in relation to levels that are known to be potentially hazardous [1] and measurements vary over several orders of magnitude. Spot measurements made near mobile phone base stations in the UK indicate median electric field strength of 120 $\mathrm{mV\,m^{-1}}$ and typical field strengths ranging from a few $\mathrm{mV\,m^{-1}}$ to around 1 $\mathrm{V\,m^{-1}}$. Very few data are available for sources other than mobile phone base stations and this is clearly an area where measurements with PEMs can add substantially to knowledge.

Achieving sufficient sensitivity to measure typical environmental signal strengths is a considerable design challenge with PEMs, especially since adequate sensitivity is needed over the entire frequency range used by sources of interest. The sensitivity of PEMs is improved by performing separate measurements in each part of the RF spectrum where sources contributing significantly to exposures transmit. There is a consensus over which bands should be measured, and 12 such bands have been identified, but this is not underpinned by a systematic investigation of the whole radio spectrum and it is possible that more bands should be measured or that some could be neglected.

Sensitivity problems with the PEMs, which lead to a large proportion of the measured data being below the detection threshold, can be overcome through the use of statistical methods. Environmental field strengths vary over several orders of magnitude from one location to another and there will usually be at least a few percent of measured values in any large dataset that are above the detection limit. This, combined with an assumption that the data are lognormally distributed, allows summary statistics such as the mean and median to be evaluated, even where these values are below the detection threshold.

The electric fields measured by PEMs are not those incident on the body. The fields are perturbed from incident values by waves being reflected from the body and shadowing effects when the wave is incident on the opposite side of the body from which the measurement is made. It is possible to calculate the extent of these effects for static scenarios through computer modelling. Such studies have shown that smaller bodies, as relevant for children's exposure, have higher whole-body specific absorption rates (power absorbed per unit body mass) and that field strength measured at the surface of the body is quite sensitive to distance of a PEM from the body.

The contribution of body-worn transmitters to personal exposures cannot be evaluated from the levels recorded by the PEM, because the exposure level relates to the distance of the PEM from the body-worn transmitter, rather than the body from the transmitter. Nevertheless, the PEM reading shows when the body-worn transmitter is active and this information can be combined with computer modelling studies to identify the exposure contribution from body-worn transmitters. This is particularly important for localised exposure scenarios where the tissue of interest is in close proximity to a body-worn transmitter.

Exposure arising from environmental transmitters is dynamic. People move around and waves are reflected by the environment such that people are exposed to multiple reflections of the same wave incident from different directions with different delays and field strengths. This is known as multipath propagation and it leads to statistical fading of exposures. Fading can counteract the shadowing effect of the body on an instrument (waves are incident from multiple directions) and so it can be an advantage in PEM measurements. However, a rigorous investigation of the relationship between absorption of RF energy (SAR) inside the body and field strength measured a few cm from the surface of the body has to take fading into account. Methods have been developed, but so far use simplistic body models because of the computational challenges with carrying out the very many static simulations that are required to build up a realistic statistical representation.

Two main population-based studies of personal exposures have been carried out so far and these have both found very similar mean total exposures for their participants: 0.11 and 0.13 $\mathrm{mW\,m^{-2}}$. These studies have partitioned the data they have acquired according to attributes of the volunteer (age, place of residence, etc.) and micro-environment where the exposure occurred (home, work, transport, etc.). Certain trends seem apparent, for example that higher exposures occurred in mobile phone transmit bands when moving on public transport and surrounded by other mobile phone users. Also, exposures were higher for people residing in urban locations than in rural ones, with peri-urban locations giving intermediate exposures.

In moving this topic forward and developing further knowledge, it will be important to carry out more studies with standardised methods for data collection and analysis. Future studies should also pay more attention to exposure metrics and appropriate use and combination of the PEM readings in different bands. WHO's 2010 RF Research Agenda ranks quantification of personal exposures from a range of RF sources and identification of the determinants of exposure in the general population as a high priority [43].

Acknowledgements

This article was written on invitation from the Fondation Santé et Radiofréquences following a presentation at a workshop held on 20–21 October 2009. The helpful comments and suggestions from the reviewers are appreciated. Thanks also are due to the Ofcom surveyors who conducted the base station measurements and to my HPA colleagues whose work has supported this paper in many ways.

References

[1] ICNIRP, Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz), Health Physics 74 (4) (1998) 494–522.
[2] S. Thomas, S. Heinrich, R. von Kries, K. Radon, Exposure to radio-frequency electromagnetic fields and behavioural problems in Bavarian children and adolescents, Eur. J. Epidemiol. 25 (2) (2010) 135–141.
[3] S. Thomas, A. Kühnlein, S. Heinrich, G. Praml, R. von Kries, K. Radon, Exposure to mobile telecommunication networks assessed using personal dosimetry and well-being in children and adolescents: the German MobilEe-study, Environ. Health 7 (4 November 2008) 54.
[4] S. Thomas, A. Kühnlein, S. Heinrich, G. Praml, D. Nowak, R. von Kries, K. Radon, Personal exposure to mobile phone frequencies and well-being in adults: a cross-sectional study based on dosimetry, Bioelectromagnetics 29 (6) (2008) 463–470.
[5] G. Berg-Beckhoff, M. Blettner, B. Kowall, J. Breckenkamp, B. Schlehofer, S. Schmiedel, C. Bornkessel, U. Reis, P. Potthoff, J. Schüz, Mobile phone base stations and adverse health effects: phase 2 of a cross-sectional study with measured radio frequency electromagnetic fields, Occup. Environ. Med. 66 (2) (2009) 124–130.
[6] A. Bürgi, P. Frei, G. Theis, E. Mohler, C. Braun-Fahrländer, J. Fröhlich, G. Neubauer, M. Egger, M. Röösli, A model for radiofrequency electromagnetic field predictions at outdoor and indoor locations in the context of epidemiological research, Bioelectromagnetics 31 (3) (2010) 226–236.
[7] P. Frei, E. Mohler, A. Bürgi, J. Fröhlich, G. Neubauer, C. Braun-Fahrländer, M. Röösli, QUALIFEX team, A prediction model for personal radio frequency electromagnetic field exposure, Sci. Total Environ. 408 (1) (2009) 102–108.
[8] P. Frei, E. Mohler, G. Neubauer, G. Theis, A. Bürgi, J. Fröhlich, C. Braun-Fahrländer, J. Bolte, M. Egger, M. Röösli, Temporal and spatial variability of personal exposure to radio frequency electromagnetic fields, Environ. Res. 109 (6) (2009) 779–785.
[9] J.F. Viel, S. Clerc, C. Barrera, R. Rymzhanova, M. Moissonnier, M. Hours, E. Cardis, Residential exposure to radiofrequency fields from mobile phone base stations, and broadcast transmitters: a population-based survey with personal meter, Occup. Environ. Med. 66 (8) (2009) 550–556.
[10] J.F. Viel, E. Cardis, M. Moissonnier, R. de Seze, M. Hours, Radiofrequency exposure in the French general population: band, time, location and activity variability, Environ. Int. 35 (8) (2009) 1150–1154.
[11] W. Joseph, G. Vermeeren, L. Verloock, M. Heredia, L. Martens, Characterisation of personal RF electromagnetic absorption for the general public, Health Physics 95 (3) (2008) 317–330.
[12] M. Röösli, P. Frei, J. Bolte, G. Neubauer, E. Cardis, M. Feychting, P. Gajsek, S. Heinrich, W. Joseph, S. Mann, L. Martens, E. Mohler, R.C. Parslow, A.H. Poulsen, K. Radon, J. Schuz, G. Thuroczy, J.-F. Viel, M. Vrijheid, Conduct of a personal radiofrequency electromagnetic field measurement study: proposed study protocol, Environ. Health 9 (20 May 2010) 23.
[13] ICNIRP, Exposure to high frequency electromagnetic fields, biological effects and health consequences (100 kHz–300 GHz), ICNIRP 16/2009 ISBN 978-3-934994-10-2, 2009, http://www.icnirp.org/PubEMF.htm.
[14] S.M. Mann, T.G. Cooper, S.G. Allen, R.P. Blackwell, A.J. Lowe, Exposure to radio waves near mobile phone base stations, Report NRPB-R321, Health Protection Agency, Chilton, UK, 2000.
[15] T.G. Cooper, S.M. Mann, M. Khalid, R.P. Blackwell, Exposure of the general public to radio waves near microcell and picocell base stations for mobile telecommunications, Report NRPB-W62, Health Protection Agency, Chilton, UK, 2004.
[16] M. Vrijheid, S. Mann, P. Vecchia, J. Wiart, M. Taki, L. Ardoino, B.K. Armstrong, A. Auvinen, D. Bédard, G. Berg-Beckhoff, J. Brown, A. Chetrit, H. Collatz-Christensen, E. Combalot, A. Cook, I. Deltour, M. Feychting, G.G. Giles, S.J. Hepworth, M. Hours, I. Iavarone, C. Johansen, D. Krewski, P. Kurttio, S. Lagorio, S. Lönn, M. McBride, L. Montestrucq, R.C. Parslow, S. Sadetzki, J. Schüz, T. Tynes, A. Woodward, E. Cardis, Determinants of mobile phone output power in a multinational study: implications for exposure assessment, Occup. Environ. Med. 66 (10) (2009) 664–671.
[17] A. Gati, A. Hadjem, M.-F. Wong, J. Wiart, Exposure induced by WCDMA mobile phones in operating networks, IEEE Transactions on Wireless Communications 8 (12) (2009) 5723–5727.
[18] Ofcom, Mobile phone base stations, Sitefinder and the audit of emissions, webpage: http://www.ofcom.org.uk/sitefinder/.
[19] M. Schubert, C. Bornkessel, M. Wuschek, P. Schmidt, Exposure of the general public to digital broadcast transmitters compared to analogue ones, Radiation Protection Dosimetry 124 (1) (2007) 53–57.
[20] K.R. Foster, M. Repacholi, Biological effects of radiofrequency fields: Does modulation matter? Radiation Research 162 (2) (2004) 219–225.
[21] J.B. Andersen, P.E. Morgensen, G.F. Pedersen, Power variations of wireless communication systems, Bioelectromagnetics 31 (4) (2010) 302–310.
[22] G. Schmid, D. Lager, P. Preiner, R. Überbacher, R. Georg, Exposure of the general public to wireless LAN applications in public places, Radiation Protection Dosimetry 124 (1) (2007) 48–52.
[23] K.R. Foster, Radiofrequency exposure from wireless LANs utilising Wi-Fi technology, Health Physics 92 (3) (2007) 280–289.
[24] E. Larchêveque, C. Dale, M.-F. Wong, J. Wiart, Analysis of electric field averaging for *in situ* radiofrequency exposure assessment, IEEE Transactions on Vehicular Technology 54 (4) (2005) 1245–1250.
[25] C. Bornkessel, M. Blettner, J. Breckenkamp, G. Berg-Beckhoff, Quality control for exposure assessment in epidemiological studies, Radiation Protection Dosimetry 140 (3) (2010) 287–293.
[26] T.G. Cooper, S.G. Allen, R.P. Blackwell, I. Litchfield, S.M. Mann, J.M. Pope, M.J. van Tongeren, Assessment of occupational exposure to radiofrequency fields and radiation, Radiation Protection Dosimetry 111 (2) (2004) 191–203.
[27] S.M. Mann, D.S. Addison, R.P. Blackwell, M. Khalid, Personal dosimetry of RF radiation: Laboratory and volunteer trials of an RF personal exposure meter, Health Protection Agency, Chilton, UK, 2005.
[28] U. Knafl, H. Lehmann, M. Riederer, Electromagnetic field measurements using personal exposimeters, Bioelectromagnetics 29 (2) (2008) 160–162.
[29] K. Radon, H. Spegel, N. Meyer, J. Klein, J. Brix, A. Wiedenhofer, H. Eder, G. Praml, A. Schulze, V. Ehrenstein, R. von Kries, D. Nowak, Personal dosimetry of exposure to mobile telephone base stations? An epidemiologic feasibility study comparing the Maschek dosimeter prototype and the Antennessa SP-090 system, Bioelectromagnetics 27 (1) (2006) 77–81.
[30] E. Cardis, I. Deltour, S. Mann, M. Moissonnier, M. Taki, N. Varsier, K. Wake, J. Wiart, Distribution of RF energy emitted by mobile phones in anatomical structures of the brain, Physics in Medicine and Biology 53 (11) (2008) 2771–2783.
[31] P.J. Dimbylow, FDTD calculations of the whole-body averaged SAR in an anatomically realistic voxel model of the human body from 1 MHz to 1 GHz, Physics in Medicine and Biology 42 (3) (1997) 479–490.
[32] P.J. Dimbylow, Fine resolution calculations of SAR in the human body for frequencies up to 3 GHz, Physics in Medicine and Biology 47 (16) (2002) 2835–2846.

[33] E. Conil, A. Hadjem, F. Lacroux, M.-F. Wong, J. Wiart, Variability analysis of SAR from 20 MHz to 2.4 GHz for different adult and child models using finite-difference time-domain, Physics in Medicine and Biology 53 (2008) 1511–1525.
[34] S. Gabriel, R.W. Lau, C. Gabriel, The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues, Physics in Medicine and Biology 41 (11) (1996) 2271–2293.
[35] R.P. Findlay, P.J. Dimbylow, Effects of posture on FDTD calculations of specific absorption rate in a voxel model of the human body, Physics in Medicine and Biology 50 (2005) 3825–3835.
[36] J. Blas, F. Angel Lago, P. Fernández, R. Mateo Lorenzo, E.J. Abril, Potential exposure assessment errors associated with body-worn RF dosimeters, Bioelectromagnetics 28 (7) (2007) 573–576.
[37] A. Bahillo, J. Blas, P. Fernández, R.M. Lorenzo, S. Mazuelas, E.J. Abril, E-field assessment errors associated with RF dosimeters for different angles of arrival, Radiation Protection Dosimetry 132 (1) (2008) 51–56.
[38] S. Iskra, R. McKenzie, I. Cosic, Factors influencing uncertainty in measurement of electric fields close to the body in personal RF dosimetry, Radiation Protection Dosimetry 140 (1) (2010) 25–33.
[39] G. Vermeeren, W. Joseph, C. Olivier, L. Martens, Statistical multipath exposure of a human in a realistic electromagnetic environment, Health Physics 94 (4) (2008) 345–354.
[40] G. Neubauer, S. Cecil, W. Giczi, B. Petric, P. Preiner, J. Fröhlich, M. Röösli, The association between exposure determined by radiofrequency personal exposimeters and human exposure: A simulation study, Bioelectromagnetics 31 (7) (2010) 535–545.
[41] M. Röösli, P. Frei, E. Mohler, C. Braun-Fahrländer, A. Bürgi, J. Fröhlich, G. Neubauer, G. Theis, M. Egger, Statistical analysis of personal radiofrequency electromagnetic field measurements with nondetects, Bioelectromagnetics 29 (6) (2008) 471–478.
[42] J. Bolte, M. Pruppers, J. Kramer, G. Van der Zande, C. Schipper, S. Fleurke, The Dutch exposimeter study: Developing an activity exposure matrix, Epidemiology 19 (6) (2008) S78–S79.
[43] WHO, WHO research agenda for radiofrequency electromagnetic fields, World Health Organization, www.who.int/peh-emf/research/agenda/en/index.html, 2010.