Assessing the compliance of emissions from MF broadcast transmitters

— with exposure guidelines

This article defines the theoretical maximum electric and magnetic field strengths and induced leg currents that people could be exposed to at MF broadcasting frequencies, without the basic restrictions being exceeded. The article is based on a contract report, prepared for BBC World Service by the Radiation Protection Division of the UK Health Protection Agency (HPA). An overview of this HPA report is provided by Mike Hate of BBC World Service.

Overview

Domestic and International broadcasters operate a number of high-power MF and HF transmitting stations around the world. Guidelines for limiting human exposure to RF radiation, which are published by ICNIRP (International Commission on Non-Ionising Radiation Protection), are formally recognized by the World Heath Organization and followed by many broadcasters.

Broadcasters have traditionally used measurements of the electric field to assess RF radiation levels and the ICNIRP guidelines provide reference field-strength levels that ensure that a more fundamental set of biologically derived “basic restrictions” are not exceeded. Of necessity these reference field strength levels have been derived by making a number of “worst case” assumptions that are not necessarily appropriate in a real situation. It was therefore thought worthwhile to consider the relationship between field strength and the basic restrictions in the practical situation of an MF or HF broadcast transmitting station.

A contract report, reproduced in full below, has been prepared by Peter Dimbylow and Simon Mann of the United Kingdom Health Protection Agency (the HPA – incorporating the former National Radiological Protection Board or NRPB), describing a simulation of a specific real situation wherein a person stands (vertical) in front of an MF transmitting antenna. The relationships between external values of the electric and magnetic field and the SAR (“Specific Absorption Rate” – of energy) in a voxel [1] model of a human being are calculated. The HPA is currently carrying out a further simulation, this time with the voxel model in front of an HF antenna. These HF results will be published in due course.

It is clear from the report that, in this specific situation, the body can be exposed to a higher MF field strength than the ICNIRP reference levels before the basic restriction, the SAR, is breached.

The results in the report must be viewed in context. A specific situation is simulated and extrapolation of the results to even closely related situations might not be appropriate. The following factors may therefore need to be considered:

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[1] The HPA (NRPB) has developed computer models of average male and female forms. These models are derived from MRI scans and model the electrical properties of the internal organs of the body, resolved to cubes of 2mm. This work is referenced in the report.

- The simulation assumes uniform conditions. In reality, the field close to a transmitting antenna, the so-called “near-field” region, is generally far from uniform, being a combination of the radiated field and the reactive field. Nevertheless, the field variation with height above ground at MF is usually much smaller than it is for the higher frequency broadcast bands. Furthermore, if a set of measurements is taken from ground level up to about 2 m and the maximum level is used, the results of the simulation should be conservative.
- Electric (E) and magnetic (H) fields are considered separately. When both are present, the effects should be added together to ensure compliance. In practice the E and H fields will not necessarily give rise to current contributions that are co-phased, or even co-sited within the body, so simple addition gives a worst case.
- The simulations also assume a perfectly conducting earth for the “grounded” and “with shoes” conditions. In practice at MF, with typical values for ground conductivity, the coupling of the field to the body will be less than the calculations suggest and so any assessment based on these should again be conservative.
- RF Hazard meters are almost invariably calibrated under far-field conditions so an additional uncertainty may arise when measurements are taken in the near-field. The field may also be perturbed, particularly when using a hand-held instrument to measure the electric field, by the body of the person taking the measurement.
- The limiting field strength might be different if, for example, the body is holding or otherwise in contact with a metallic object for a significant amount of time (relative to the ICNIRP 6 minute SAR averaging time). An assessment of the activities carried out in the locations of interest may therefore be appropriate.

Other points to note in connection with the use of the findings in the report for RF Hazard assessment purposes are:

- The ICNIRP guidelines allow the reference levels to be exceeded only if adverse indirect effects such as shocks and burns can be excluded.
- The ICNIRP guidelines do not address the possibility of interference with medical implants such as cardiac pacemakers, which can occur below the reference levels.
- The possible detonation of electro-explosive devices (detonators) and the risk of flammable materials being ignited are not covered by the ICNIRP guidelines but by other standards.

It will also be seen from the report that the difference between the ICNIRP occupational electric field reference levels and those calculated *(Fig. 6.1)* is much smaller than the corresponding difference for the magnetic field *(Fig. 6.3).* This is not a function of the latest computational approaches or the high resolution models used by the HPA but reflects the way in which ICNIRP has set these reference levels. The magnetic field at frequencies below 10 MHz does not contribute significantly to the risk of shocks and burns that form a major basis for limiting occupational exposure to electric fields in that frequency range.

It is also clear that the limiting factor is the SAR in the leg. Since the leg SAR and the leg current are related it is possible that a more direct assessment of the SAR could be made by measuring the leg/ankle current. This would have the advantage of eliminating many unknown factors such as ground conductivity and the near-field effects mentioned above. The report includes the ankle current data *(Table 5.3)* needed for carrying out such an assessment of the SAR and commercial instruments are available for making the necessary measurements. Broadcasters will need to validate such instruments and the associated measurement methods.

This work was commissioned from the HPA by the BBC. Any comments or queries should be directed to the BBC World Service (attn Mike Hate – **michael.hate@bbc.co.uk**) and not to the HPA.

The similar study looking at HF transmitters will be published in a future edition of **EBU Technical Review**.

Mike Hate
BBC World Service

The HPA MF report

1. Introduction

1.1. Background

BBC World Service operates high-power radio broadcast transmitters in several countries around the world. The antennas connected to the transmitters produce strong ***electric*** and ***magnetic*** fields, both of which reduce in strength with increasing distance. In general, the area in the immediate vicinity of the transmitting antennas is controlled by virtue of it being inside a perimeter fence; however, members of the public can be exposed to electric and magnetic fields outside the fence.

Various organizations have promulgated advice in the form of guidelines on limiting people's exposure to electromagnetic fields (ICNIRP, 1998 [1]; NRPB, 2004 [2]). Such advice contains basic restrictions – which should not be exceeded – on the ***induced current density*** (J) and the ***specific energy absorption rate*** (SAR) in the body. There are various regulatory and voluntary drivers to comply with this advice in different parts of the world and BBC World Service has an interest in ensuring that its operations do not cause the accepted basic restrictions to be exceeded.

The relationships between electric and magnetic field strengths, as calculated or measured at a position of exposure, and also the ***basic restrictions*** are complicated and depend on frequency. From analysis of these relationships, the guidelines contain ***reference levels*** in terms of field strengths below which exposure should not lead to the basic restrictions being exceeded, even under the strongest coupling conditions between the body and the field.

For simplicity of application, the reference levels are presented as envelope curves that offer varying degrees of conservatism according to frequency. In some frequency bands, the application of reference levels as action levels may result in larger regions of non-compliance than might result if comparison with the basic restrictions on exposure were to be assessed using the latest computational modelling techniques.

1.2. Project Scope

1.2.1. Aims

This project aimed, more specifically, to define the theoretical maximum electric and magnetic field strengths and induced leg currents that people could be exposed to at the MF band frequencies used by BBC World Service without the basic restrictions being exceeded. This should be helpful in establishing more precise boundaries to regions around antennas for compliance with exposure guidelines.

1.2.2. Methods

A review of the calculations performed originally at NRPB (now HPA's Radiation Protection Division) – relating external electric and magnetic fields and induced leg currents to basic restrictions in the body – has been made for frequencies between 500 and 1500 kHz. The calculations have been performed using the latest computational approaches, together with anatomically realistic ***voxel*** (volume pixel) models of the human body. They assume that the electric field is uniform and vertically polarized. The calculated external field values and leg currents required to produce the internal basic restrictions in the body are presented and compared with the external field reference levels in the guidelines.

1.2.3. Frequencies of interest

BBC World Service supplied technical information to the authors about its MF transmitting stations operated by VT Communications on its behalf. These transmitters are located at Orfordness (Suffolk, UK), Lady's Mile and Zygi (Cyprus) and also A'Seela (Oman). They have powers ranging from 200 kW to 800 kW and their frequencies are shown in *Table 1.1*.

Table 1.1
MF transmitter sites operated by VT Communications on behalf of BBC World Service

Site name	Transmitter name	Frequency (kHz)
Lady's Mile	Cyprus 1	639
Orford Ness	UK 1	648
A'Seela	Oman 1	702
Lady's Mile	Cyprus 2	720
Orford Ness	UK 2	1296
Zygi	Cyprus 3	1323
A'Seela	Oman 2	1413

1.2.4. Report structure

Section 2 sets out the ICNIRP basic restrictions and reference levels. The anatomically realistic voxel models of the body used in dosimetry calculations are described in *Section 3*. Reviews of the calculations published in the open literature for induced current density and SAR are presented in *Sections 4* and *5*, respectively. A comparison of the calculated external fields with the ICNIRP reference levels is made in *Section 6* and conclusions are drawn in *Section 7*.

2. EMF Guidelines

2.1. ICNIRP basic restrictions

The ICNIRP guidelines (ICNIRP, 1998 [1]) have separate restrictions and reference levels for those people who are exposed occupationally, and for members of the general public. Restrictions on the effects of electromagnetic fields are based on biological considerations. These restrictions are mostly in terms of internal quantities in the body such as the induced current density and the specific energy absorption rate (SAR) which are difficult to measure directly. Between 0.5 and 1.5 MHz, the basic restriction on current density in the head, neck and trunk is $f / 100$ mA m^{-2} where f is the frequency in MHz. This current density is averaged over 1 cm^2.

The ICNIRP guidelines intend to avoid the effects of induced electric currents on functions of the central nervous system, such as the control of movement and posture, memory, reasoning and visual processing. Therefore, when investigating maximum current densities in the body in relation to standards, it is appropriate to consider only the brain, spinal cord and retina. The basic restrictions on SAR are 0.4 W kg^{-1} averaged over the whole-body, 10 W kg^{-1} averaged over 10 g in the head and trunk, and 20 W kg^{-1} averaged over 10 g in the limbs. SAR values can be averaged over any 6-minute period. The ICNIRP basic restrictions for occupational and public exposure are given in *Tables 2.1* and *2.2*.

Table 2.1
ICNIRP restrictions for occupational exposure

Basic restriction	Value	Averaging
Current density in the head, neck and trunk	*f* (Hz) / 100 mA m^{-2}	Over 1 cm^2 of brain, spinal cord or retina
SAR averaged over the whole-body	0.4 W kg^{-1}	In any 6-minute period
SAR in the head and trunk	10 W kg^{-1}	Over 10 g in any 6-minute period
SAR in the limbs	20 W kg^{-1}	Over 10 g in any 6-minute period

Table 2.2
ICNIRP restrictions for public exposure

Basic restriction	Value	Averaging
Current density in the head, neck and trunk	*f* (Hz) / 500 mA m^{-2}	Over 1 cm^2 of brain, spinal cord or retina
SAR averaged over the whole-body	0.08 W kg^{-1}	In any 6-minute period
SAR in the head and trunk	2 W kg^{-1}	Over 10 g in any 6-minute period
SAR in the limbs	4 W kg^{-1}	over 10 g in any 6-minute period

2.2. ICNIRP reference levels

Reference levels are values of external fields provided for comparison with measured field quantities for investigating whether compliance with basic restrictions is achieved. However, if the measured field values are greater than the relevant reference levels, it does not necessarily follow that the basic restrictions are exceeded. *Tables 2.3* and *2.4* give the reference levels for the ICNIRP guidelines over the MF frequency range for electric and magnetic fields, respectively.

Table 2.3
Electric field reference levels in V m^{-1} (rms)

Frequency (MHz)	ICNIRP occupational	ICNIRP public
0.5	610	87
0.6	610	87
0.7	610	87
0.8	610	87
0.9	610	87
1.0	610	87
1.1	555	83.0
1.2	508	79.4
1.3	469	76.3
1.4	436	73.5
1.5	407	71.0

Table 2.4
Magnetic flux density reference levels in µT (rms)

Frequency (MHz)	ICNIRP occupational	ICNIRP public
0.5	4.0	1.84
0.6	3.33	1.53
0.7	2.86	1.31
0.8	2.5	1.15
0.9	2.22	1.02
1.0	2.0	0.92
1.1	1.82	0.84
1.2	1.67	0.77
1.3	1.54	0.71
1.4	1.43	0.66
1.5	1.33	0.61

3. Voxel models

The state-of-the-art approach to deriving reference levels is to solve the Maxwell's equations numerically ... in fine resolution, anatomically realistic, models of the body. These are usually derived from medical imaging data and are referred to as voxel (volume pixel) phantoms. The phantom structure is a 3D array of cells or voxels which each have a tag denoting the discrete tissue type or the surrounding air.

The HPA (formerly the NRPB) male phantom is known as **NORMAN**. A complete description of the acquisition of the medical imaging data and its segmentation into tissue types can be found in Dimbylow (1996 [3], 1997a [4]). The raw MRI data were acquired from a series of continuous partial body scans of a single subject. The blocks of data were conjoined by rescaling, translation and rotation to form an entire body. The MRI slices were 256 x 256 pixel images in the axial plane. The data volume was rescaled and interpolated to produce cubical voxels of ~ 2 mm. The 8-bit grey scale images were segmented unambiguously into discrete tissue types. The phantom was normalized to be 1.76 m tall and to have a mass of 73 kg the values for "reference man" (ICRP, 2002 [5]). Hence, the name was derived from "normalized MAN".

The height fixes the vertical voxel dimension, 2.021 mm, and the horizontal dimensions, 2.077 mm, are then fixed by the mass. There are 8.3 million voxels in the body. The tissues types are skin, fat, muscle, tendon, bone, trabecular bone, blood, brain, spinal cord, cerebrospinal fluid, sclera, humour, lens, oesophagus, stomach-contents, duodenum, small intestine, lower large intestine, upper large intestine, pancreas, gall bladder, bile, liver, spleen, kidney, bladder, urine, prostate, testis, breast,

Abbreviations

FDTD	Finite Difference Time Domain
HPA	Health Protection Agency (UK) http://www.hpa.org.uk/
ICNIRP	International Commission on Non-Ionizing Radiation Protection http://www.icnirp.de/
ICRP	International Commission on Radiological Protection http://www.icrp.org/
MF	Medium-Frequency
MRI	Magnetic Resonance Imaging
NRPB	(former) National Radiological Protection Board (UK)
rms	Root-Mean-Square
SAR	Specific energy Absorption Rate
SPFD	Scaler Potential Finite Difference

thymus, thyroid, adrenals, heart, lung, air and background domain. An evaluated review of the dielectric properties of all the tissue types in NORMAN was performed by Gabriel (1995, 1996a-c [6][7][8][9]). A 4-Cole-Cole dispersion model was fitted to the data for each tissue type to parameterise the conductivity and permittivity as a function of frequency.

A female voxel model, **NAOMI** has recently been developed and is described in detail in Dimbylow (2005) [10]. The primary medical imaging data were derived from a high-resolution MRI scan of a 1.65 m tall, 23 year-old female subject with a mass of 58 kg. The model was rescaled to a height of 1.63 m and a mass of 60 kg, the dimensions of the ICRP reference adult female (ICRP, 2002 [5]). In NORMAN, the brain was treated as one tissue type. In this female model the grey and white matters were differentiated separately. The structure of the thyroid had to be inserted manually using anatomical textbooks. The new tissues in NAOMI are vagina, uterus, ovary, cartilage in the nose and the brain differentiated into grey and white matter. Prostate and testis are particular to NORMAN.

4. Calculations of induced current density

4.1. Applied magnetic fields

Dimbylow (1998) [11] calculated current density in the fine resolution (2 mm) NORMAN phantom for uniform magnetic fields incident from the front, side and top of the body for frequencies from 50 Hz to 10 MHz. Both the impedance and SPFD methods were used to provide mutual corroboration. In the impedance method (Gandhi et al, 1984 [12]; Orcutt and Gandhi, 1988 [13]), the target body is split into cuboid cells or ***voxels***, which are then further differentiated into a 3-D network of impedances. The time-varying magnetic field impresses a voltage around the closed loop of each face. A system of coupled equations for the loop currents on the orthogonal faces of the cells is produced and can be solved iteratively. The electric fields along the edges of the cuboid cell are then obtained to produce an average value in the cell and thence a value for the current density.

More recently the Scalar Potential Finite Difference (SPFD) method has been introduced (Dawson et al, 1996 [14]; Dawson and Stuchly, 1997 [15]). This method incorporates the applied magnetic field source as a vector potential term in the electric field. This equation for the electric field is then transformed into a scalar potential form, which is then solved using finite differences. This continuous equation can be mapped onto a 3D domain of cells. The finite-difference technique can then be used to define the potential at nodes where the cells meet in terms of potentials at neighbouring nodes and the conductivities of neighbouring cells evaluated at half-node points, i.e. on the edges half-way between nodes, along with vector potential values at these half-nodes. The equation for the potential can then be solved iteratively or by matrix methods. A feature of both methods is that the computational space is confined to only the voxels of the body.

At 50 Hz the impedance and SPFD methods agree to within 2% for AP (front-to-back), 3% for LAT (side-to-side) and 1% for TOP (top-to-bottom) orientation. The scalar potential method requires less computational memory and is much quicker than the impedance method so this was chosen to perform the full range of calculations up to 10 MHz. The outer layer of the eye in NORMAN was not initially differentiated from the humour. The retina is important because of the induction of phosphenes. Therefore, because the humour and sclera have quite different conductivities, the outer layer of the eye was reclassified as sclera. The rear part of this shell was then considered to be the retina for the analysis of induced current density. Values were calculated for the current density averaged over 1 cm^2 in muscle, heart, brain, spinal cord and retina.

4.2. Applied electric fields

The difficulty in calculating the interaction of low frequency electric fields with the body, as opposed to magnetic fields, is that the body perturbs the applied field and this perturbation must be accommodated in the specification of the boundary conditions. Dimbylow (2000) [16], using NORMAN, solved the quasistatic potential equation on a series of nested sub-grids decreasing from 32 mm to 2 mm. The outer region of the domain extended sufficiently so that the perturbation in the applied field, due to the phantom, was small at the periphery whilst the grid near and in the phantom was small enough to model the structural details. The solution of the potential equation is divided into two parts. First, the coupling between the externally applied electric field and the human body, which is deemed to be a conductor at low frequencies, is calculated to provide the surface charge. This charge is then used as a boundary condition to calculate the internal potential and hence induced fields and current densities in the body at a resolution of 2 mm. Current density distributions were calculated for uniform, low-frequency vertically-aligned electric fields for grounded and isolated conditions from 50 Hz to 10 MHz.

4.3. Numerical values for NORMAN and NAOMI

The recently developed female model, NAOMI has been applied to the calculation of induced current densities from applied low frequency magnetic and electric fields (Dimbylow, 2005 [10]) using the numerical methods described above. The calculated current density results averaged over a 1 cm^2 surface for NAOMI were compared and contrasted in this study with those for NORMAN (The NORMAN values have been recalculated in this article to obtain information on induced electric fields and so may be slightly different from Dimbylow (1998) [11])

Table 4.1 presents the calculated external magnetic flux density required to generate the ICNIRP occupational restrictions on induced current density averaged over 1 cm^2 in the brain, spinal cord and retina. The minimum values in brackets are 1/5th of the main minimum values, corresponding to the ICNIRP public restrictions. AP refers to the external field aligned from the front to the back of the body, LAT from side to side and TOP from head to toe. The magnetic field aligned side-to-side (LAT) gives the highest current density values and they occur in the retina. When the field is aligned from front-to-back (AP) the body presents the greatest cross-sectional area and so the maximum induced fields will occur in this condition but the calculations here refer to the brain, spinal cord and retina only. The retina has a high conductivity and is near the front of the head and so will yield the maximum current density for the LAT condition. The maximum values in NORMAN are greater than those in NAOMI. This effect is due in part to the larger cross-sectional area normal to the magnetic field alignment presented by NORMAN. A relative scaling factor for the cross-sectional area is ~ (73 kg / 60 kg)$^{2/3}$ = 1.14. This is a macroscopic factor and the detailed anatomical structure of the models determines the exact variations.

Table 4.1
Calculated external magnetic flux density required to generate restrictions on induced current density averaged over 1 cm^2

Frequency (MHz)	Current density restriction (A m^{-2})	Calculated external fields (μT)						
		NAOMI			NORMAN			Minimum
		AP	LAT	TOP	AP	LAT	TOP	
0.1	**1.0**	138	94.3	166	111	81.3	114	81.3 (16.2)
1	**10.0**	122	85.5	143	100	71.9	101	71.9 (14.4)
10	**100.0**	91.7	64.1	106	73.5	54.3	78.7	54.3 (10.9)

The values in brackets are for a reduction of basic restrictions by a factor of 5. AP refers to the external field aligned from the front to the back of the body, LAT from side to side and TOP from head to toe.

Table 4.2
Calculated external electric fields required to generate restrictions on induced current density averaged over 1 cm^2

Frequency (MHz)	Current density restriction (A m^{-2})	Calculated external fields (Vm^{-1})		
		NAOMI	NORMAN	Minimum
0.1	1.0	2480	2570	2480 (495)
1	10.0	2610	2700	2610 (522)
10	100.0	3110	2160	2160 (433)
The values in brackets are for a reduction of basic restrictions by a factor of 5. The models are grounded.				

Table 4.2 presents the calculated external electric field values required to generate the ICNIRP occupational restrictions on induced current density averaged over 1 cm^2 in the brain, spinal cord and retina. Isolated and grounded conditions are considered. The NORMAN values have been recalculated (Dimbylow, 2005 [10]) and convergence has been improved by imposing the value of the short-circuit current from the external charge distribution on the internal potential calculations. The current, across a horizontal section, flowing to ground depends on the sum of the surface charge on the body above that section. The current density will tend to increase as one goes down the body, with enhancements in the knees and particularly the ankles. The value of the short-circuit current depends on the size and surface shape of the body and not on its internal structure or conductivity values. A relative scaling factor for the cross-sectional area between NORMAN and NAOMI is ~ $(73\text{ kg} / 60\text{ kg})^{2/3} = 1.14$, which agrees very well with the calculated short-circuit currents of 14. 76 μA per kV m^{-1} for NORMAN and 12.89 μA per kV m^{-1} for NAOMI at 50 Hz. The maximum values in the brain, spinal cord and retina averaged over 1 cm^2 occur in the retina for both models. The values are very similar and depend on the detailed anatomical structure of the top part of the model heads. The current densities in the body for isolated conditions are about half those for grounded conditions.

5. Calculations of SAR

5.1. *Whole-body averaged SAR*

The Finite-Difference Time-Domain, FDTD method (see e.g. Taflove, 1995 [17]) provides a direct solution of the coupled, time-dependent Maxwell curl equations. The method follows the time evolution of the propagation, reflection and absorption of electromagnetic waves in a domain comprising the target and surrounding space. The domain is divided into a 3D lattice of cuboid cells which are assigned discrete electrical properties. The components of the E field are positioned on the middle of the edges and the components of the H field are at the middle of the faces of the lattice cells. An explicit second-order finite-difference procedure then leap-frogs, evaluating E from H and vice-versa at alternate half-time steps until equilibrium has been reached.

In the following calculations, this was taken to be the maximum of two periods of the wave or 10 traversals of the largest dimension of the domain. A domain enclosing the target and a boundary condition on the surface of the domain must be chosen to mimic numerically the unbounded region outside the domain by absorbing the outgoing scattered waves. The perfectly matcher layer (pml)-based boundary conditions of Berenger (1994) [18] were used. The technique is based on splitting the electric and magnetic fields into two in the absorbing boundary region. This gives additional degrees of freedom for the specification of material parameters. Thus it is possible to create a nonphysical absorbing medium, adjacent to the external mesh boundary, in which waves of arbitrary frequency and angle of propagation are caused to decay rapidly while maintaining the velocity and impedance of the media from which they propagated. A Huygens surface (Merewether *et al*, 1980 [19]) was implemented in the FDTD code (i) to allow the description of arbitrary incident fields, (ii) to separate the scattered field that is required for the boundary conditions from the total field required for the FDTD formulation and (iii) to connect the pml layers to the inner region of the domain. Electric and magnetic currents are defined on the Huygens surface which produce the correct total fields inside the surface but just the scattered fields outside the surface.

The FDTD method has been applied (Dimbylow, 1997a [4]) to NORMAN to provide a comprehensive set of whole-body averaged SAR for grounded and isolated in air conditions from 1 MHz to 1 GHz for vertically-polarized plane-wave exposure. Calculations were also performed for NORMAN wearing shoes on a ground plane as an input to the Dimbylow (1997b) [20] work on ankle SAR. The shoes were represented by placing a 2 cm layer of rubber ($\varepsilon_r = 3.2$) under the feet. It was not then computationally tractable to perform FDTD calculations directly at a cell size of 2 mm. Therefore, the phantom was rescaled to produce 6 mm, 1 cm and 2 cm models with the properties of the rescaled cells being taken as the volume average of the basic component voxels. The period of the wave is proportional to the inverse of the frequency and so at the lower frequencies more time steps are required. Therefore, 2 cm resolution was used at the lowest frequencies. The computational effort required is proportional to the reciprocal of the 4th power of the cell size. The lowest frequencies at which values of the whole-body averaged SAR were reported in this study are 1 and 2 MHz. Although not part of this BBC contract, extra calculations were performed at 0.5 and 1.5 MHz for ease of interpolation in the MF range.

[Calculations were later performed of the whole-body averaged SAR (Dimbylow, 2002 [21]) from 100 MHz up to 3 GHz by using the basic ~ 2 mm resolution of NORMAN. At lower frequencies, a 4 mm resolution discrete voxel version was used with an overlap to 200 MHz and it was found that the whole-body averaged SAR is a robust quantity with respect to model resolution. However, these calculations only extended down to 10 MHz.]

Table 5.1 presents the calculated whole-body averaged SAR for an applied field of 1 V m^{-1} (rms) and the derived external electric field required to produce a restriction of 0.4 W kg^{-1}. Note the SAR is proportional to the square of the electric field. The ICNIRP occupational guidelines have a restriction of 0.4 W kg^{-1}. The ICNIRP public exposure guidelines have a restriction that is a factor of 5 lower at 0.08 W kg^{-1}.

Table 5.1
Calculated whole-body averaged SAR and the external electric field required to produce a restriction of 0.4 W kg^{-1}

Frequency (MHz)	SAR (μW kg^{-1}) applied field of 1 V m^{-1}			Electric field (V m^{-1})		
	Grounded	With shoes	Isolated	Grounded	With shoes	Isolated
0.5	0.180	0.0828	0.0161	1490 (667)	2200 (982)	4980 (2230)
1	0.258	0.196	0.0341	1250 (557)	1430 (639)	3420 (1530)
1.5	0.710	0.420	0.0640	750 (335)	976 (436)	2500 (1120)
2	1.18	0.663	0.119	582 (260)	777 (347)	1830 (820)

The values in brackets are for a reduction of basic restrictions by a factor of 5, i.e. a reduction in field values by $5^{1/2}$

5.2. *Localised SAR in the leg*

The maximum of the induced layer current occurs in the lower limbs for plane wave irradiation of the body, at frequencies around and below the whole body resonance. The ankle region has a narrow cross-section with little high conductivity muscle. The sections consist mainly of low-conductivity bone, fat and tendon. Consequently, there is a channelling of the current through the high conductivity muscle, which produces high, localised SAR values in the muscle. It is not computationally tractable to perform FDTD calculations of the whole body, at the basic 2 mm resolution, at frequencies below 100 MHz.

The localised SAR averaged over 10 and 100 g in the lower limb has been calculated at a 2 mm resolution (Dimbylow, 1997b [20]) for a unit current injected through the open upper boundary of a partial leg model using a finite-difference solution of the quasistatic potential equation from 0.1 to 80 MHz. An initial solution for the scalar potential was defined on the 3D mesh of cells defining the leg. The solution was then iteratively refined using the computational molecule of the potential equation and the associated boundary conditions. A known current was injected into the top boundary of the leg and extracted through the open bottom boundary. The bottom 220 slices of the whole body model, NORMAN were extracted to make a voxel model of the lower leg.

The ICNIRP recommendations specify averaging SAR over 10 g of any contiguous shape. The method to obtain this quantity was as follows. The voxel with the maximum absorption rate was chosen from each horizontal section. Then a search was performed of its 6 neighbours to find the one with the highest absorption rate. The power and masses were summed and then a search was performed among the neighbours of those two voxels, etc to finally obtain a connected region of voxels for which the mass is greater than or equal to 10 g.

The localised SAR averaged over 10 g in the lower arm has been also been calculated (Dimbylow, 2001 [22]) as a function of the current injected through the open upper boundary of the arm model. This consists of 147 slices from NORMAN, extending from a plane through the hand at the "knuckles" to just below the elbow.

Table 5.2 (on the next page) takes ankle currents from the whole body FDTD calculations at 2 cm resolution and folds them with the values of localised SAR for an injected current of 100 mA derived from the finite difference potential calculations in the lower leg at a resolution of 2 mm. This produces values of localised SAR in the leg in terms of the applied electric field for vertically polarized plane wave irradiation. The external electric field required to produce a restriction of 20 W kg^{-1} is calculated from this SAR value. The values in brackets are for a reduction of basic restrictions by a factor of 5, i.e. 4 W kg^{-1} for ICNIRP occupational exposure.

Table 5.2
Calculated SAR in the leg averaged over 10 g and the external electric field required to produce a restriction of 20 W kg^{-1}

Frequency (MHz)	Ankle current (mA per V m^{-1})	SAR (W kg^{-1}) for 100 mA	SAR (μW kg^{-1}) for 1 V m^{-1}	Electric field (V m^{-1})
Grounded				
0.5	0.132	16.5	28.7	834 (373)
1	0.137	15.3	28.7	835 (373)
1.5	0.257	13.4	88.5	475 (213)
2	0.337	13.0	148	368 (165)
With shoes				
0.5	0.0865	16.5	12.3	1270 (569)
1	0.109	15.3	18.2	1050 (469)
1.5	0.184	13.4	45.4	664 (297)
2	0.236	13.0	72.4	526 (235)
Isolated				
0.5	0.0253	16.5	1.06	4350 (1950)
1	0.0355	15.3	1.93	3220 (1440)
1.5	0.0579	13.4	4.49	2110 (944)
2	0.0777	13.0	7.85	1600 (714)
The values in brackets are for a reduction of basic restrictions by a factor of 5, i.e. a reduction in field values by $5^{1/2}$				

The ICNIRP guidelines do not have ankle current reference levels in the frequency range 0.5 – 1.5 MHz. However, ankle current could be used as a surrogate measure for localised SAR in the legs for well grounded situations. *Table 5.3* derives ankle current reference levels from column 3 of *Table 5.2*.

Table 5.3
Calculated ankle currents required to produce restrictions on localised SAR averaged over 10 g in the leg

Frequency (MHz)	Ankle current (mA)	
	For 20 W kg^{-1}	For 4 W kg^{-1}
0.5	110	49.2
1	114	51.1
1.5	122	54.6
The ICNIRP occupational restriction is 20 W kg^{-1} and the ICNIRP public restriction is 4 W kg^{-1} both averaged over 10 g.		

6. Comparison of calculations with reference levels

The next part of this section comprises four pages each with a table and a corresponding figure comparing guidelines with calculated external field values that would produce a basic restriction on internal dose quantities. The basic restrictions considered are induced current density in the brain, spinal cord and retina; whole-body averaged SAR and localised SAR in the leg. (The localised SAR in the leg is the most restrictive of the localised SAR quantities.)

Table 6.1 and *Fig. 6.1* consider the ICNIRP occupational exposure electric field reference levels. The ICNIRP reference levels provide a conservative estimate of the basic restrictions. The localised SAR in the leg is the most restrictive quantity. If one considers the limiting case to be grounded with bare feet then the fields required to produce the basic restriction on localised SAR in the leg are ~ 830 V m^{-1} from 0.5 to 1 MHz, decreasing to ~ 470 V m^{-1} at 1.5 MHz. The more realistic case with shoes on yields external fields of ~ 1300 V m^{-1} at 0.5 MHz, ~ 1050 V m^{-1} at 1 MHz and ~ 660 V m^{-1} at 1.5 MHz.

Table 6.2 and *Fig. 6.2* consider the ICNIRP public exposure electric field reference levels. The basic restrictions are a factor of 5 down on those for occupational exposure. The ICNIRP reference levels provide a very conservative estimate of the basic restrictions. The localised SAR in the leg is the most restrictive quantity. If one considers the limiting case to be grounded with bare feet then the fields required to produce the basic restriction on localised SAR in the leg are ~ 370 V m^{-1} from 0.5 to 1 MHz, decreasing to ~ 200 V m^{-1} at 1.5 MHz. The more realistic case with shoes on yields external fields of ~ 570 V m^{-1} at 0.5 MHz, ~ 470 V m^{-1} at 1 MHz and ~ 300 V m^{-1} at 1.5 MHz.

Table 6.3 and *Fig. 6.3* consider the ICNIRP occupational exposure magnetic flux density reference levels. The calculations of SAR are based upon plane wave irradiation, i.e. there are both electric and magnetic field components. The derived values are given in terms of the magnetic field component but include the contribution to SAR from the electric field in the plane wave. The ICNIRP reference levels provide a very conservative estimate of the basic restrictions. The localised SAR in the leg is the most restrictive quantity. If one considers the limiting case to be grounded with bare feet then the fields required to produce the basic restriction on localised SAR in the leg are ~ 28 μT from 0.5 to 1 MHz, decreasing to ~ 16 μT at 1.5 MHz. The more realistic case with shoes on yields external fields of ~ 42 μT at 0.5 MHz, ~ 35 μT at 1 MHz and ~ 22 μT at 1.5 MHz.

Table 6.4 and *Fig. 6.4* consider the ICNIRP public exposure magnetic flux density reference levels. The ICNIRP reference levels provide a very conservative estimate of the basic restrictions. The localised SAR in the leg is the most restrictive quantity. If one considers the limiting case to be grounded with bare feet then the fields required to produce the basic restriction on localised SAR in the leg are ~ 12 μT from 0.5 to 1 MHz, decreasing to ~ 7.1 μT at 1.5 MHz. The more realistic case with shoes on yields external fields of ~ 19 μT at 0.5 MHz, ~ 16 μT at 1 MHz and ~ 10 μT at 1.5 MHz.

Table 6.1
Comparison of ICNIRP occupational exposure electric field reference levels with calculated fields required to generate basic restrictions

Frequency (MHz)	ICNIRP reference level (V m^{-1})	Calculated external electric fields (V m^{-1}) from basic restrictions						
		Whole-body SAR			Leg SAR			Current density
		Grounded	With shoes	Iso-lated	Grounded	With shoes	Iso-lated	
0.1	610							2480
0.5	610	1490	2200	4980	834	1270	4350	
0.6	610							
0.7	610							
0.8	610							
0.9	610							
1.0	610	1250	1430	3420	835	1050	3220	2610
1.1	555							
1.2	508							
1.3	469							
1.4	436							
1.5	407	750	976	2500	475	664	2110	
2.0	305	582	777	1830	368	526	1600	
10	61							2160

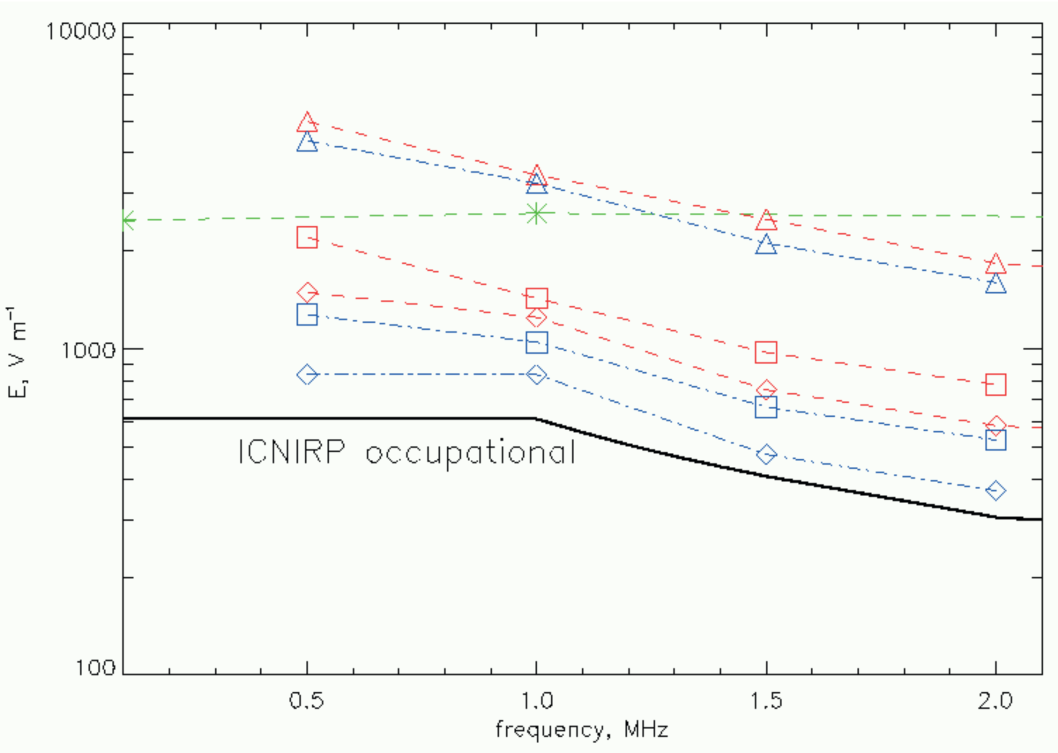

Figure 6.1
Comparison of ICNIRP occupational exposure electric field reference levels (solid line) with calculated fields required to generate basic restrictions. The green asterisks are for current density. The blue symbols are for leg SAR, the red symbols are for whole-body SAR. Diamonds are for grounded conditions, squares are with shoes and triangles for isolated conditions.

Table 6.2
Comparison of ICNIRP public exposure electric field reference levels with calculated fields required to generate basic restrictions

Frequency (MHz)	ICNIRP reference level ($V\ m^{-1}$)	Calculated external electric fields ($V\ m^{-1}$) from basic restrictions						
		Whole-body SAR			Leg SAR			Current density
		Grounded	With shoes	Isolated	Grounded	With shoes	Isolated	
0.1	87							495
0.5	87	667	982	2230	373	569	1950	
0.6	87							
0.7	87							
0.8	87							
0.9	87							
1.0	87	557	639	1530	373	469	1440	522
1.1	83.0							
1.2	79.4							
1.3	76.3							
1.4	73.5							
1.5	71.0	335	436	1120	213	297	944	
2.0	61.5	260	347	820	165	235	714	
10	28							433

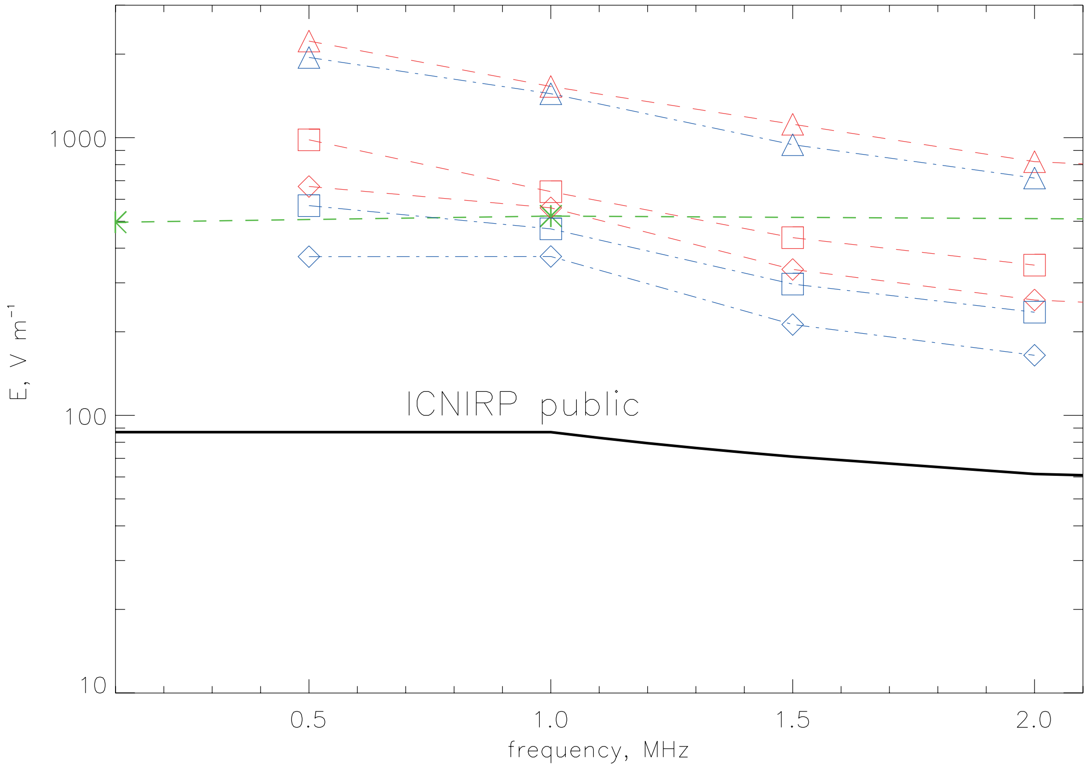

Figure 6.2
Comparison of ICNIRP public exposure electric field reference levels (solid line) with calculated fields required to generate basic restrictions. The green asterisks are for current density. The blue symbols are for leg SAR, the red symbols are for whole-body SAR. Diamonds are for grounded conditions, squares are with shoes and triangles for isolated conditions.

Table 6.3
Comparison of ICNIRP occupational exposure magnetic flux density reference levels with calculated fields required to generate basic restrictions

Frequency (MHz)	ICNIRP reference level (µT)	Calculated external magnetic fields (µT) from basic restrictions						
		Whole-body SAR			Leg SAR			Current density
		Grounded	With shoes	Iso-lated	Grounded	With shoes	Iso-lated	
0.1	20							81.3
0.5	4	49.8	73.3	166	27.8	42.5	145	
0.6	3.33							
0.7	2.86							
0.8	2.5							
0.9	2.22							
1.0	2	41.7	47.7	114	27.9	35.0	107	71.9
1.1	1.82							
1.2	1.67							
1.3	1.54							
1.4	1.43							
1.5	1.33	25.0	32.6	83.4	15.8	22.2	70.4	
2.0	1	19.4	25.9	61.1	12.3	17.5	53.4	
10	0.2							54.3

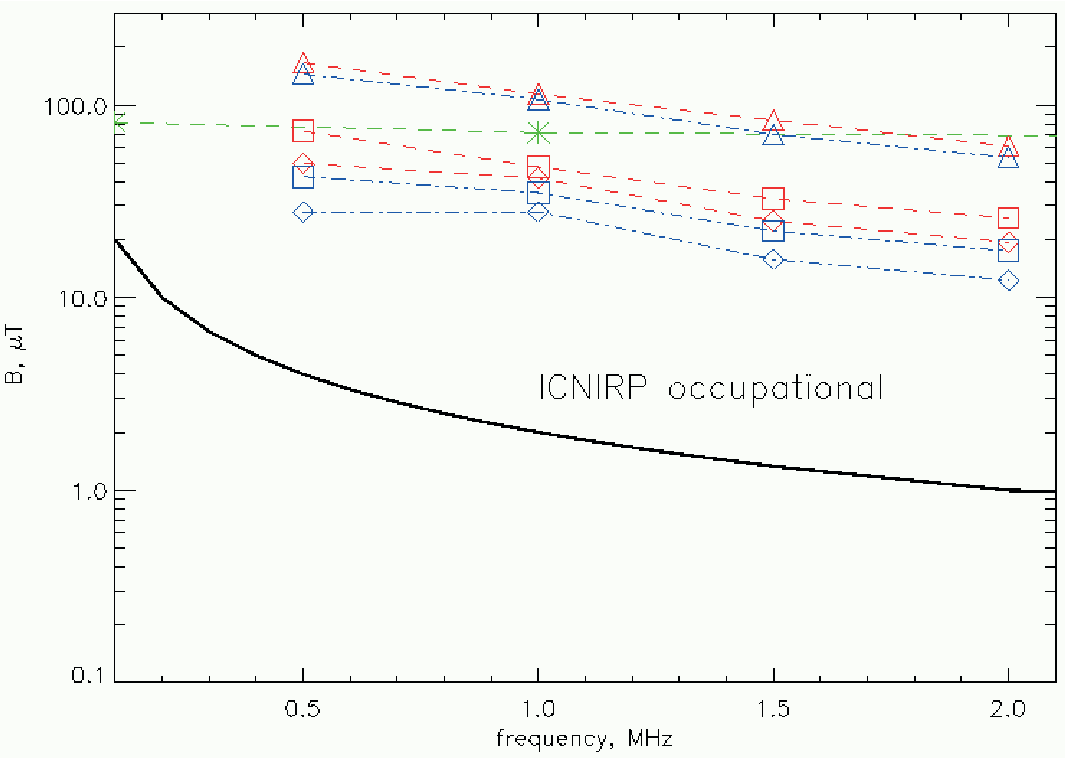

Figure 6.3
Comparison of ICNIRP occupational exposure magnetic flux density reference levels (solid line) with calculated fields required to generate basic restrictions. The green asterisks are for current density. The blue symbols are for leg SAR, the red symbols are for whole-body SAR. Diamonds are for grounded conditions, squares are with shoes and triangles for isolated conditions.

Table 6.4
Comparison of ICNIRP public exposure magnetic flux density reference levels with calculated fields required to generate basic restrictions

Frequency (MHz)	ICNIRP reference level (µT)	Calculated external magnetic fields (µT) from basic restrictions						
		Whole-body SAR			Leg SAR			Current density
		Grounded	With shoes	Isolated	Grounded	With shoes	Isolated	
0.1	6.25							16.2
0.5	1.84	22.3	32.8	74.2	12.4	19.0	64.8	
0.6	1.53							
0.7	1.31							
0.8	1.15							
0.9	1.02							
1.0	0.92	18.6	21.3	51.0	12.5	15.7	47.9	14.4
1.1	0.84							
1.2	0.77							
1.3	0.71							
1.4	0.66							
1.5	0.61	11.2	14.6	37.3	7.07	9.93	31.5	
2.0	0.46	8.68	11.6	27.3	5.50	7.83	23.9	
10	0.092							10.9

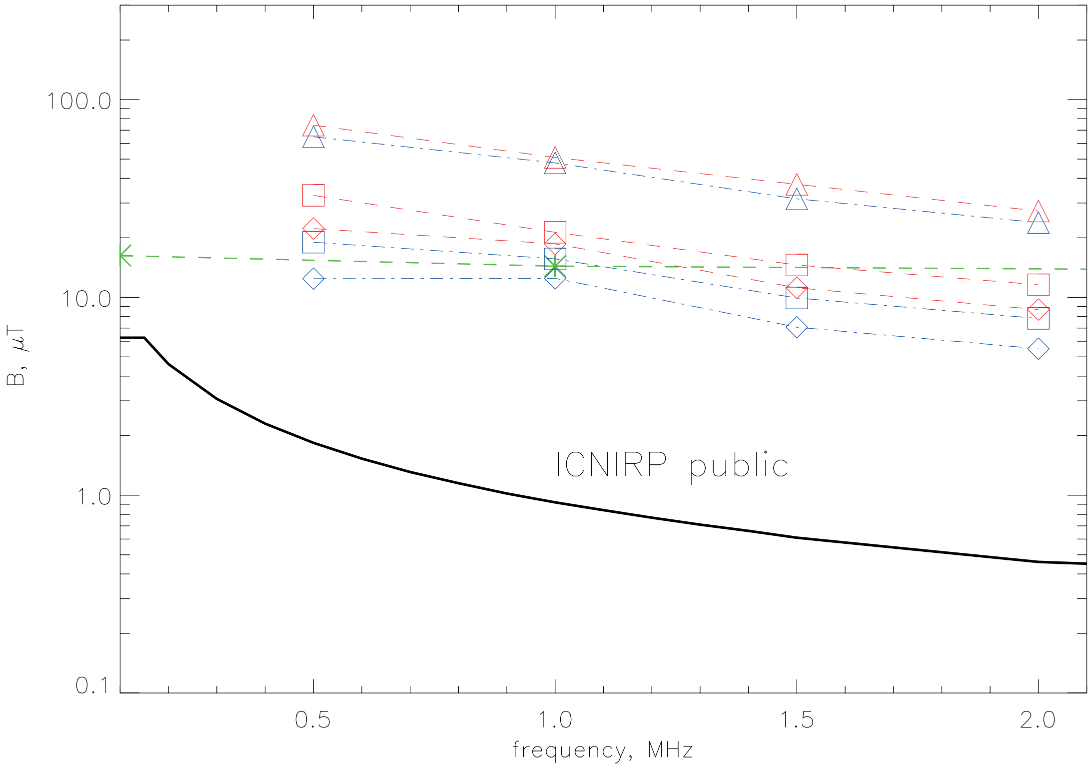

Figure 6.4
Comparison of ICNIRP public exposure magnetic flux density reference levels (solid line) with calculated fields required to generate basic restrictions. The green asterisks are for current density. The blue symbols are for leg SAR, the red symbols are for whole-body SAR. Diamonds are for grounded conditions, squares are with shoes and triangles for isolated conditions.

Conclusions

This project has defined the theoretical maximum electric field strengths and magnetic flux densities that people could be exposed to at the MF band frequencies used by BBC World Service without the basic restrictions being exceeded. This should be helpful in establishing more precise boundaries to regions around antennas for compliance with exposure guidelines.

A review of the calculations performed at NRPB (now the Radiation Protection Division of the Health Protection Agency) relating external electric and magnetic fields to basic restrictions in the body has been made for frequencies from 500 to 1500 kHz. Specifically, the review has included calculations of the induced current density in the brain, spinal cord and retina, the whole body averaged SAR and localised SAR in the leg. It was assumed that for the MF antennas the electric field would be vertically polarized. The calculations had been performed on the voxel (volume pixel) models, NORMAN and NAOMI produced at NRPB. The calculated external field values required to produce the internal basic restrictions in the body have been compared with the ICNIRP occupational and public exposure reference levels.

The NRPB in its recent advice on limiting exposure to electromagnetic fields (NRPB, 2004 [2]) recommends the adoption of the ICNIRP guidelines. The ICNIRP electric field reference levels provide a conservative estimate of the basic restrictions for both occupational and public exposure. The localised SAR in the leg is the most restrictive quantity.

The ICNIRP magnetic flux density reference levels provide a conservative estimate of the basic restrictions. The localised SAR in the leg is the most restrictive quantity.

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