Assessing the compliance of emissions from HF 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 HF 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

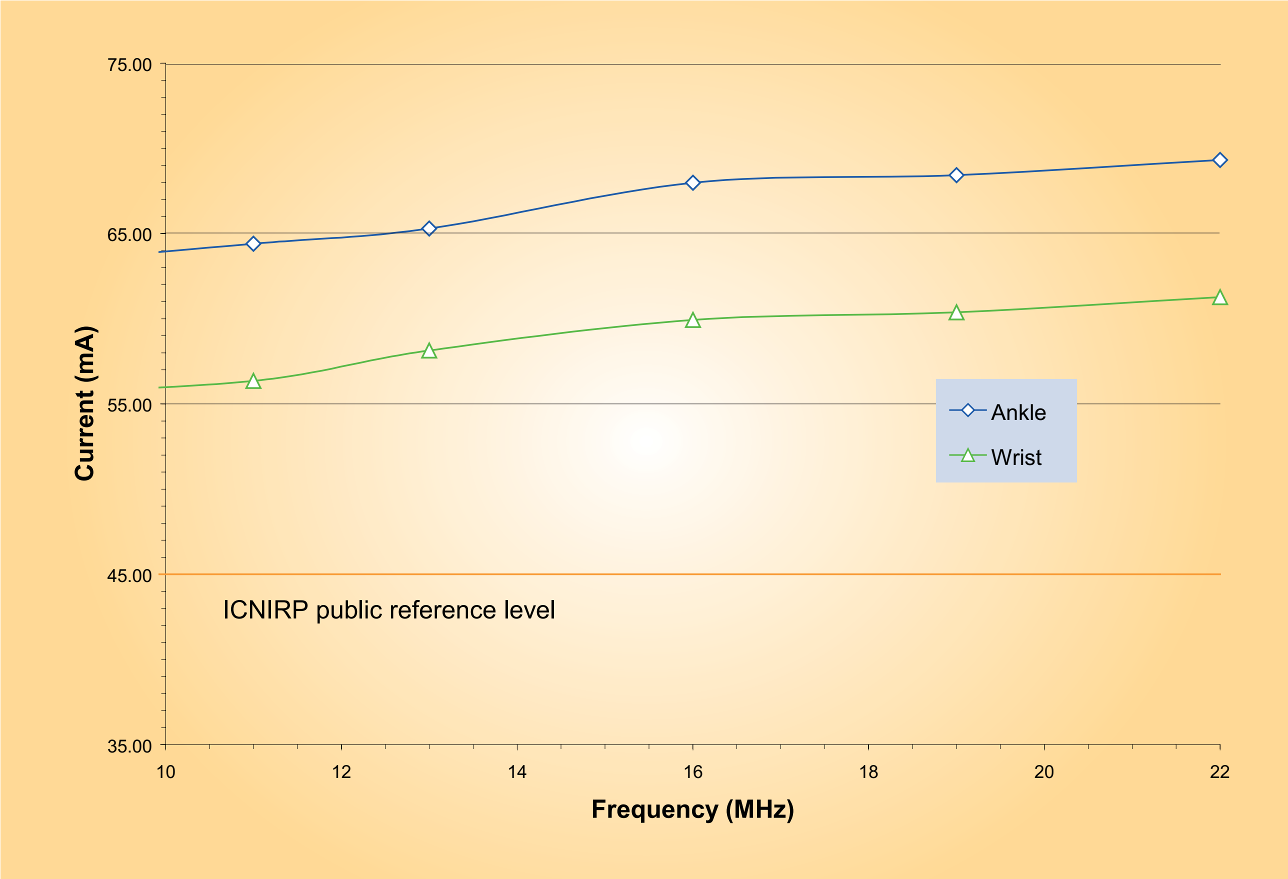
A study commissioned by BBC World Service on the assessment of emissions from MF broadcast transmitters against exposure guidelines was published in the last edition (January 2006) of **EBU Technical Review** [1]. A further study, with the same aim of helping broadcasters assess compliance with ICNIRP exposure guidelines, has now been completed for the case of HF broadcast transmitters. This new study, also commissioned from the UK Health Protection Agency (HPA) deals with the situation where a person is standing in the field from an HF array, using the same basic simulation methods as for the previous MF study.

Making assessments against the basic restrictions for HF transmissions is much more complicated, but potentially more worthwhile, than doing this in the case of MF transmitters. The difference arises because the ICNIRP reference levels are based on the worst case condition where a body is aligned with the field. This is appropriate for a person standing near a vertically polarized MF transmitting antenna, but not a horizontally polarized HF transmission. Previous work suggests that the coupling at HF is substantially lower when the field is at 90 degrees to the body and therefore the reference levels could be particularly conservative in this case.

In practice, the field from a typical HF broadcast transmitting antenna usually also has a vertical component. Whilst this may be relatively small compared with the main horizontal component, the coupling to the body is much greater and so it was felt that, for the purposes of the study, it could not be ignored. It was also recognized that a person's posture affects the coupling of the body to the field. In particular, it was expected that, for horizontal polarization, there could be a significant increase if the arms were outstretched. This is because the arms would then be aligned with the field and have an overall electrical length similar to that of the person's height.

The HPA study therefore considered both vertical and horizontal polarization. In the case of vertical polarization, the three conditions as used for the MF study were considered, i.e. grounded, with shoes and isolated. For horizontal polarization, the grounding of the feet was not considered to be very relevant and so the isolated condition only was studied, but for an "arms out" posture as well as the usual "arms down" case. The contract report, prepared by Richard Findlay, Peter Dimbylow and Simon Mann of the HPA is reproduced in full below.

The report concludes that, for a vertical electrical field, the ICNIRP electric field reference level is conservative at the frequencies in the lower HF bands but is not low enough to provide compliance



with the basic restrictions at the frequencies in the higher HF bands. However, there is also an ICNIRP limb current reference level specified for frequencies above 10 MHz, and the calculations show that this ensures compliance at the higher frequencies. The graph shows the ankle currents and wrist currents, corresponding to the SAR restrictions in the limbs, in relation to the ICNIRP induced current reference levels for public exposure.

The report also concludes that, for the horizontal electric field component, the reference levels are conservative even for the “arms out” posture. Moreover, in the case of the “arms down” posture, the ICNIRP reference levels are significantly lower than those needed to ensure compliance with the basic restrictions.

The detailed results from this HF study need to be considered in the context of the actual conditions pertaining to a particular broadcasting station, even more so than the results of the MF study. The reasons for this are as follows:

- In the case of a typical HF antenna, the assessment must consider both the horizontal and the vertical component of the field. Whilst the predominant field may be largely horizontally polarized, this has a much lower coupling to the body than the vertical component. The significance of each component is likely to vary considerably from one antenna to another and also with location relative to the antenna and the posture being assumed for the person exposed.
- The simulations assume uniform field conditions. At HF broadcast sites, the field variation over the dimensions of the human body is much larger than it is at MF, partly due to the significant variation with height above ground level. Measurements or calculations are traditionally carried out at a height of 1.5 m or 2 m, and these should be appropriate for assessing the worst case “arms out” horizontally polarized component of the field. However, the use of measurements or calculations carried out at these heights is likely to lead to an over-estimate of the absorbed energy for the vertically polarized field from an HF transmitting station, compared with that shown in the report. In this case, some form of averaging over the body height should therefore be worthwhile.
- The most restrictive quantity at HF is less certain than it is at MF. For the vertical component of the field, the localised SAR in the leg is the most restrictive quantity; as it is with MF. For the

worst case "arms out" posture at HF, the localised SAR in the wrist is the most restrictive quantity. The whole body SAR is however only marginally less restrictive for this condition. In the case of the "arms down" posture, the whole body SAR is the most restrictive. The field from a typical HF antenna usually contains both horizontal and vertical components, especially at close distances. In general therefore, it would be unsafe to make any assumption about the most restrictive quantity. Unfortunately this means that assessments against the basic restrictions will often need to include SAR in the leg, the wrist and the whole body.

- 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 at HF are:

- The report has shown that, at the higher frequencies used for broadcasting in the HF bands, the ICNIRP limb current reference levels need to be considered as well as the field strength reference levels, when a significant vertically polarized electric field component is present. The limb current reference levels are however shown to be conservative at HF and so an assessment against the basic restrictions may still be worthwhile.
- 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.

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

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Abbreviations

FDTD Finite Difference Time Domain
HF High-Frequency
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 National Radiological Protection Board (UK)
SAR Specific energy Absorption Rate

The HPA HF report

1. Introduction

1.1. Background

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

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has issued advice in the form of guidelines on limiting people's exposure to electromagnetic fields (ICNIRP, 1998 [2]). Such advice contains basic restrictions on the induced current density and specific energy absorption rate (SAR) in the body tissues, which should not be exceeded. 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 field strengths, as calculated or measured at a position of exposure, and the basic restrictions are complicated and depend on frequency. From analysis of these relationships, the guidelines contain reference levels in terms of field strengths and induced limb currents 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, 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. Also, the reference levels are calculated for the body aligned with the field, i.e. vertically polarized exposure for a standing position, since this configuration is expected to give rise to maximum coupling between the body and a wave.

1.2. Project Scope

1.2.1. Aims

This project aims to more specifically define the theoretical maximum horizontally and vertically polarized electric field strengths and induced leg currents for plane wave irradiation that people could be exposed to at the HF 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

Finite-difference time-domain (FDTD) calculations of SAR have been performed on the voxel (volume pixel) phantom, ***NORMAN***, a human male anatomical model produced at the NRPB, now the Radiation Protection Division of the Health Protection Agency (HPA). Each ~2 mm cube voxel has a tag which identifies the discrete tissue type of that particular voxel. The phantom consists of ~9 million voxels and is segmented into 37 tissue types. The exact dimensions of the voxels have been scaled so that the height (1.76 m) and the mass (73 kg) agree with the values of reference man in ICRP 89 (2002) [3].

1.2.3. Frequencies of interest

BBC World Service supplied technical information to the authors about HF transmitting stations operated by VT Communications on its behalf. These transmitters are shown in *Table 1.1*.

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

Location	Site name	Power (kW)
Ascension Island		250
Oman	A'Seelah	250
Cyprus	Zygi	250 & 300
Seychelles	Grand Anse	250
Singapore	Kranji	100 & 250
Thailand	Nakon Sawan	250

The calculations have been performed at 7 frequencies spanning the range of interest, i.e. 6, 8, 11, 13, 16, 19 and 22 MHz. The period of the wave is proportional to the inverse of the frequency and so at the lower frequencies more time steps were required to reach equilibrium in the FDTD method. At the frequencies considered it was not computationally tractable to perform FDTD calculations directly at a cell size of 2 mm. Therefore, the phantom has been re-scaled to a 4 mm voxel size to make the calculations practical.

The purpose of these calculations was to predict the external electric field values and induced leg currents that correspond to restrictions on SAR in the body. The calculated field and leg current values were then compared with reference values from the guidelines. Calculations for horizontally polarized electric fields have been included as it is the predominant field orientation from the antennas used by BBC World Service in this frequency range.

The sets of calculations performed were

1) Vertically polarized plane wave irradiation of NORMAN, with shoes and barefoot on a perfectly conducting ground plane.

2) Vertically polarized plane wave irradiation of NORMAN isolated in space.

3) Horizontally polarized plane wave irradiation of NORMAN isolated in space.

4) Horizontally polarized plane wave irradiation of NORMAN, isolated in space, with the arms stretched out horizontally to the side of the body.

1.2.4. Report structure

In this report, *Section 2* outlines the ICNIRP basic restrictions and reference levels. The voxel models of the body used in dosimetry calculations are described in *Section 3*. The FDTD method and calculations are presented in *Sections 4* and *5* respectively with conclusions of the project in *Section 6*.

2. Electromagnetic field guidelines

2.1. ICNIRP basic restrictions

ICNIRP provides guidelines for limiting the exposure to electromagnetic fields to prevent adverse effects on health (ICNIRP, 1998 [2]). Above 100 kHz these adverse health effects are mainly due to the heating of tissues. The quantity used as a surrogate measure of temperature rise in the restriction of exposure to fields between 100 kHz and 10 GHz is the specific energy absorption rate, SAR. SAR is defined as the rate of absorption of electromagnetic energy per unit mass and is measured in watts per kilogram (W kg^{-1}). Separate restrictions and reference levels exist within the guidelines for those occupationally exposed and for the general public.

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} (up to 10 MHz)	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

The basic restrictions on SAR for occupational exposure 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. For public exposure these reduce to 0.08 W kg^{-1} averaged over the whole body, 2 W kg^{-1} averaged over 10 g in the head and trunk and 4 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* for the frequencies studied in this work.

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} (up to 10 MHz)	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. *Table 2.3* presents the reference levels for the ICNIRP guidelines over the HF frequency range studied in this project for external electric fields.

Table 2.3
ICNIRP reference levels, V m^{-1} (rms), for occupational and public exposure to electric fields

Frequency (MHz)	Occupational exposure Electric field value (V m^{-1})	Public exposure Electric field value (V m^{-1})
6	101.7	35.5
8	76.3	30.8
11	61	28
13	61	28
16	61	28
19	61	28
22	61	28

Additionally, there exist reference levels for currents induced in any limb at frequencies between 10 and 110 MHz. These are presented in *Table 2.4*.

Table 2.4
ICNIRP occupational and public reference levels for induced limb currents, mA

Frequency (MHz)	Occupational exposure current (mA)	Public exposure current (mA)
10 MHz – 110 MHz	100	45

3. Voxel models

The technique used to investigate the relationship between SAR in the body and external electric field exposure in this project was the application of the FDTD method to anatomically correct voxel phantoms (see e.g. Dimbylow, 1997a [4]). The NRPB (now part of the HPA) developed its own numerical phantom, ***NORMAN*** (normalized MAN). This model was derived from a series of continuous partial body MRI scans of a male subject. It is a 3D array of ~2 mm voxels. A complete description of the phantom can be found in Dimbylow 1996 and 1997a [5][4].

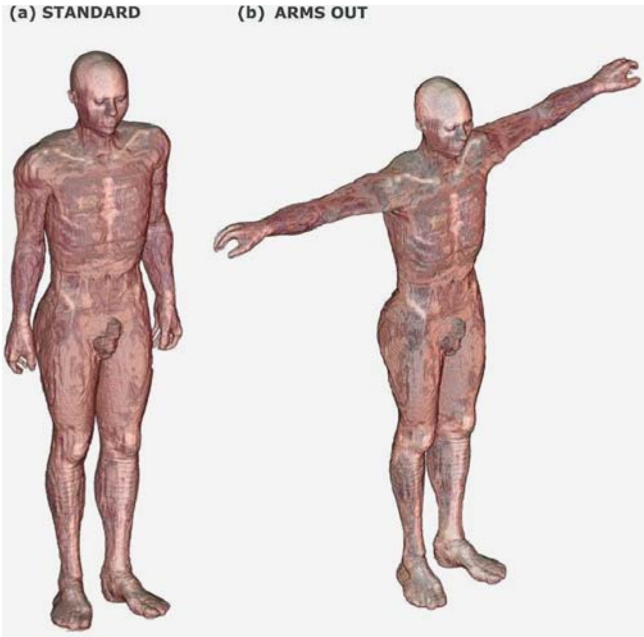

Figure 3.1
Images of the NORMAN voxel phantom in the (a) standard, arms vertically to the side and (b) arms horizontally to the side postures

Calculations of electromagnetic field exposure are usually performed for a vertically polarized plane wave incident on a voxel phantom in a standing position with arms vertically to the side. This is a recognized condition in which the absorption of the electric field is at a maximum. However, changes in the polarization of the incident field and posture of the human body can alter the way in which this field is absorbed. A voxel phantom with arms stretched horizontally to the side of the body was produced in this project to investigate the effects of horizontally polarized plane wave irradiation. Images of both phantoms are shown in *Fig. 3.1*.

The arms out horizontally to the side posture was derived from the original NORMAN voxel model by removing and re-attaching the arms. This was achieved by writing code which enabled the files representing the limbs to be manipulated into the correct orientation.

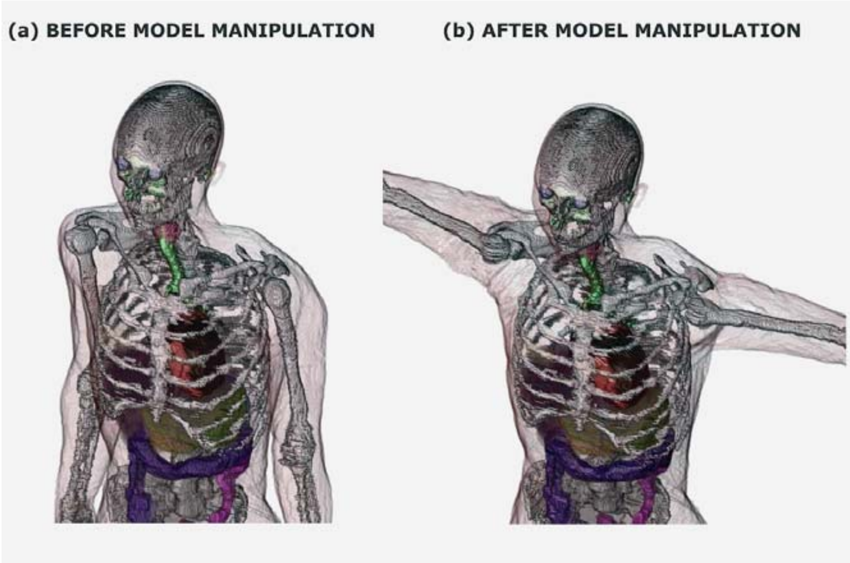

Figure 3.2
Tissue-enhanced views of the upper body area (a) *before* and (b) *after* model manipulation

The steps involved included creating a sub-volume of the arm, rotating this through 90°, re-attaching and manually editing the section to ensure tissue continuity. Manual editing involved changing the argument of the displaced voxels produced by the procedure above. This value links the voxel to its relevant tissue properties. The most important factors in the process were to maintain the correct length of the arms and provide electrical continuity of tissues when they were re-attached. *Fig. 3.2* shows a tissue enhanced image of the model in the arms out horizontally to the side posture with views before and after file manipulation.

The horizontal dimensions of this model were adjusted to achieve the correct mass of 73 kg, the mass for “reference man” as defined in ICRP 89 (2002) [3]. The original resolution of the model in the arms down to the side posture was a vertical dimension of 2.021 mm and a horizontal dimension of 2.077 mm resulting in a domain of 277 voxels (side to side) by 148 voxels (front to back) by 871 voxels (high). The production of the arms out posture increased the size of the computational domain to 928 x 148 x 871. The dielectric properties of tissues used in NORMAN were provided by Gabriel et al (Gabriel 1995 [6], Gabriel et al 1996a [7], 1996b [8], 1996c [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.

4. Finite-difference time-domain method

The calculation of fields induced within the body involves the solution of the coupled, time-dependent Maxwell curl equations:

$$\vec{\nabla} \times \vec{H} = \sigma \vec{E} + \varepsilon \frac{\partial \vec{E}}{\partial t} \qquad \text{(Equation 1)}$$

$$\vec{\nabla} \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} \qquad \text{(Equation 2)}$$

... where $\vec{E}$ is the electric field and $\vec{H}$ is the magnetic field, σ is the electrical conductivity, ε is the permittivity and μ is the permeability.

The FDTD method (Taflove 1995 [10]) provides a direct method to solve these equations.

An explicit second-order finite difference procedure evaluates $\vec{E}$ and $\vec{H}$ at alternate half-time steps throughout a computational domain made up of a 3D grid of cells. These cells represent both the voxel phantom and surrounding space with each cell assigned discrete electrical properties. The procedure is continued until convergence of the solution has been reached. In these calculations this was taken to be the maximum of two periods of the wave or ten traversals of the largest dimension of the domain. The perfectly matched layer (pml) based boundary conditions (Berenger 1994 [11]) were used. It involves creating a non-physical absorbing medium, adjacent to the external grid boundary, which causes waves of arbitrary frequency and angle of propagation to decay rapidly whilst maintaining the velocity and impedance of the media from which they propagated. A Huygens surface (Merewether et al 1980 [12]) was implemented in the code to allow the description of arbitrary incident fields, to separate the scattered field that is required for the boundary conditions from the total field required for the FDTD formulation and also to connect the pml layers to the inner region of the domain.

The implementation of the FDTD method was tested by comparing results gained from FDTD calculations with the analytical Mie series solution (Neuder 1979 [13]) for a sphere. The sphere was homogeneous and of 30 cm diameter, the approximate width of a human torso, constructed from 4 mm cubical cells. The tissue properties for the sphere were an estimated average for whole-body conductivity and permittivity, adjusted for the particular frequency used in the calculation. As an example of a quantitative comparison in the HF range, *Fig. 4.1* shows the results at 22 MHz for the vertically aligned electric field (E_z) along the central axis of the sphere from front to back. The incident field was 1 V m^{-1}.

The average absolute percentage difference between the FDTD method and the Mie series at this frequency for E_z was 1.1%.

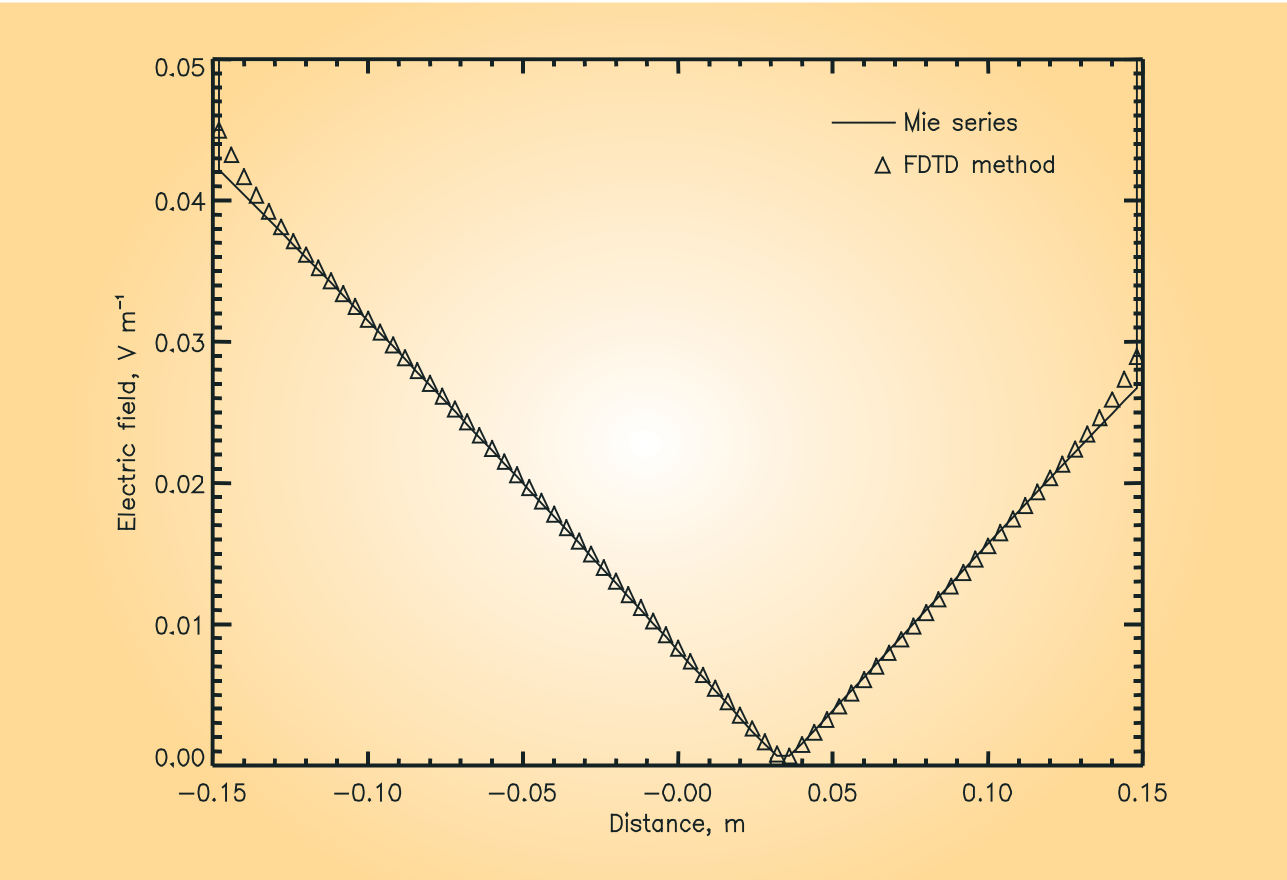

Figure 4.1
A comparison of the electric field in a 30 cm diameter sphere calculated by the Mie series (line) and the FDTD method (symbols). The plot is along the central axis of the sphere from front to back.
The incident field was 1 V m^{-1}

5. Calculations

5.1. Whole-body SAR

The latter part of this section consists of tables and corresponding figures for the various relationships discussed here. Firstly, whole-body SAR calculations were performed at 4 mm resolution, from 6 MHz to 22 MHz. Plane wave irradiation incident to the front (antero-posterior AP) of the numerical phantom was employed in all cases. SAR values were calculated for vertically polarized electric fields with the model isolated, wearing shoes on a ground plane and barefoot on a ground plane. The shoes were represented by placing a 2 cm layer of rubber (ε_r = 3.2) under the feet. Calculations were also carried out for horizontally polarized electric fields with the model under isolated conditions.

Table 5.1 (see page 14) presents the whole-body averaged SAR values calculated for the two postures studied in this work. The highest SAR values are seen when the incident electric field is vertically polarized and the model is barefoot on a ground plane. These calculated values rise steadily from 6 MHz to 22 MHz, towards a peak at approximately 35 MHz, the quarter-wave resonance condition for the grounded, adult male phantom in the standard, arms vertically to the side posture. When the electric field is horizontally polarized, the whole-body averaged SAR for an adult in this posture is over an order of magnitude lower than that calculated for a vertically polarized field. However, these values are significantly increased if the arms of the voxel model are aligned with the field by positioning them horizontally to the side of the body. Indeed, the values calculated for this posture are similar to those obtained for a vertically polarized incident field when the isolated model has the arms vertically to the side. As expected, the SAR for an adult wearing shoes on a ground plane lies between that calculated for the same posture when isolated and barefoot on a ground plane. The whole-body SAR values calculated are presented in *Fig. 5.1*.

Table 5.2 presents the ankle currents from the whole-body FDTD calculations at 4 mm. These ankle currents are used in the calculation of localised SAR in the leg in terms of the applied electric field, outlined in the next section.

Tables 5.3 and *5.4*, along with the plots in *Figs 5.3* and *5.4*, present the derived electric field levels required to produce the restriction on whole-body averaged SAR for ICNIRP occupational and public exposure. All curves representing these calculations lie within ICNIRP reference levels, therefore the reference levels in these cases provide a conservative estimate of the basic restrictions. The situation in which the strongest coupling conditions exist between the body and the field is barefoot on a ground plane when exposed to a vertically polarized electric field. In this situation, the field values required to produce the ICNIRP occupational restriction on whole-body averaged SAR varied from 286 V m^{-1} at 6 MHz to 83.8 V m^{-1} at 22 MHz. This compares with ICNIRP occupational electric field reference levels of 101.7 V m^{-1} at 6 MHz, and 61 V m^{-1} for frequencies above 10 MHz. Similarly, the electric field values required to produce the ICNIRP public restriction on whole-body averaged SAR varied from 128 V m^{-1} at 6 MHz to 37.5 V m^{-1} at 22 MHz. The ICNIRP public electric field reference levels are 35.5 V m^{-1} at 6 MHz, and 28.0 V m^{-1} for frequencies above 10 MHz.

When the field was horizontally polarized, the electric field values required to produce the ICNIRP basic restrictions were significantly above reference levels. In the arms out horizontally to the side posture, the strongest coupling condition for horizontal polarization, calculated values required to produce occupational restrictions on whole-body averaged SAR varied from 917 V m^{-1} at 6 MHz to 271 V m^{-1} at 22 MHz. The calculated electric field values required to produce the ICNIRP public restriction on whole-body averaged SAR varied from 410 V m^{-1} at 6 MHz to 121 V m^{-1} at 22 MHz, over four times higher than the ICNIRP reference level of 28.0 V m^{-1}.

5.2. Localised limb SAR

The ankle region has a narrow cross-section with little high conductivity muscle. This area comprises mainly of low conductivity bone, fat and tendon. There is a channelling of the current through the high conductivity tissues, and so the maximum induced current tends to occur in this region, at frequencies around or below the whole-body resonance value. Because of this, it is an important region to consider when assessing the ICNIRP localised limb SAR restriction. Also considered is the wrist region, as the maximum induced current can occur here if the arms are extended and the incident field is horizontally polarized.

The localised SAR averaged over 10 g in the limbs have been calculated at 2 mm resolution for a unit current injected through the open upper boundary of a partial leg or arm model using a finite-difference solution of the quasi-static potential equation from 0.1 to 80 MHz (Dimbylow 1997b [14] and 2000 [15]). An initial solution for the scalar potential was defined on the 3D mesh of cells defining the limb. 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 limb and extracted through the open bottom boundary.

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.

Table 5.5 combines the values of localised SAR over 10 g from finite-difference potential calculations in the lower leg with values of ankle current *(Table 5.2)* to give values of the applied electric field required to generate 20 W kg^{-1}, the ICNIRP occupational restriction level for localised limb SAR. This value (E_a) is given by:

$$E_a = \frac{10^3}{I_a}\left(\frac{20}{SAR(10g)}\right)^{1/2} \qquad \text{(Equation 3)}$$

... where the ankle current I_a is in mA per V m^{-1}, and $SAR(10g)$ is the maximum SAR averaged over 10 g in the leg, with units of W kg^{-1} per A.

In a similar way, the values of applied electric fields required to generate 4 W kg^{-1}, the ICNIRP public restriction level for localised limb SAR, have been calculated and are presented in *Table 5.6*. *Figs 5.5* and *5.6* show graphically the field values required for occupational and public restrictions, respectively. These calculated values can be compared with fields required to produce whole-body SAR restrictions in *Tables 5.3* and *5.4*. When the incident electric field is vertically polarized, the leg SAR is the limiting quantity for isolated, shod and barefoot on a ground plane.

Fig. 5.7 shows the calculated wrist currents for the various orientations, *Figs 5.8* and *5.9* present the electric field values required to generate occupational and public SAR restrictions in the arms. These figures show that, when the incident electric field is horizontally polarized and the arms are held out horizontally, the localised SAR in the arm is the limiting quantity as the highest limb currents occur in the wrist and not the ankles. The whole body SAR is however very close to being the limiting quantity under these conditions and becomes it with this polarization in the arms down posture

Ankle current can be related to localised SAR in the leg. *Tables 5.10* and *5.11*, along with the plots in *Figs 5.10* and *5.11*, present these relationships for occupational and public restrictions. The relationships are independent of electric field polarization and model posture.

Fig. 5.12 shows the regions of the body in which the incident field is absorbed at 22 MHz. The SAR in each voxel is displayed for the two postures, normalized to the maximum value in the whole phantom by means of a colour map. The map is a rainbow spectrum ranging from violet for the lowest absorbed power to red for the highest. This was then stretched to enhance the lower part of the scale. When the field is aligned vertically at a frequency below that of the resonance condition, absorption occurs in the areas made up of low conductivity tissues in the lower limbs, i.e. the knees and ankles. Similarly if the field is horizontally polarized the field is absorbed in the low conductivity tissue areas aligned with the field, in this case the wrists and elbows.

As has been seen, the electric field levels required to produce ICNIRP restrictions on limb currents, when compared with the ICNIRP electric field reference levels, generally provide a conservative estimate. The exception to this is the barefoot on a ground plane exposure condition when the field is vertically polarized. At 22 MHz the required electric field value to produce the occupational restriction is 58.3 V m^{-1}, under the reference level of 61 V m^{-1}, at that frequency. Similarly, under the same exposure conditions, the electric field value required to produce public restrictions on limb SAR does not comply with the reference level. However, ICNIRP reference levels also exist for currents induced in limbs *(Table 2.4)*. These are 100 mA for occupational and 45 mA for public exposure between 10 and 110 MHz. As an example, at 22 MHz the electric field value required for the public basic restriction of 4 W kg^{-1} averaged over 10 g in the leg is 26.1 V m^{-1} when the model is barefoot on a ground plane. The corresponding external electric field value for a limb current of 45 mA is 16.9 V m^{-1}, hence the limb current reference levels would provide compliance with basic restrictions on localised SAR averaged over 10 g in the leg.

5.3. Induced current density

The focus of this work has been on calculating SAR in the body as a result of various exposure conditions and comparing these calculations with the ICNIRP guidelines. However, restrictions on induced current density in the head, neck and trunk also exist for frequencies up to 10 MHz *(Table 2.1)*. To investigate which is the more restrictive quantity in the frequency range studied here, calculations of induced current density in NORMAN (Dimbylow and Mann 2005 [16]) have been compared with calculated SAR. Induced current density values in the voxel model were achieved by solving the quasi-static potential equation on a series of nested sub-grids decreasing from 32 mm to 2 mm (Dimbylow 2000 [15]). The solution of this equation is split 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 produce 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 2 mm resolution.

Table 5.12 compares the calculated electric field values required to produce ICNIRP restrictions on whole-body SAR, leg SAR averaged over 10 g and induced current density averaged over 1 cm^2 at 1 and 10 MHz. These values are for the NORMAN phantom under grounded conditions for vertically polarized exposure. Comparison of these values clearly indicate that SAR is the more restrictive quantity in this frequency range. The electric field value required to produce ICNIRP occupational restrictions on whole-body SAR is approximately half that required to produce induced current density restrictions at 1 MHz, with the difference rising to over ten times smaller at 10 MHz.

6. Conclusions

Values of SAR and limb currents between 6 MHz and 22 MHz have been calculated for plane wave, horizontally and vertically polarized electric field exposure, where the voxel model is isolated in air, wearing shoes or barefoot on a ground plane. Calculations were also performed for a new model of the human body with arms stretched horizontally to the side, derived from the voxel phantom, NORMAN, in the arms vertically to the side posture.

For the exposures studied, comparisons of electric field strengths calculated from whole-body averaged SAR values with ICNIRP field reference levels show that these reference levels provide a conservative estimate of the ICNIRP restrictions. The condition in which the coupling between the body and the field is at its strongest is the barefoot grounded voxel model when exposed to a vertically polarized electric field. The electric field values required to produce the ICNIRP occupational restriction on whole-body averaged SAR under these conditions varies from 286 V m^{-1} at 6 MHz to 83.8 V m^{-1} at 22 MHz. This compares with ICNIRP occupational electric field reference levels of 101.7 V m^{-1} at 6 MHz, and 61 V m^{-1} for frequencies above 10 MHz.

Similarly, the electric field values required to produce the ICNIRP public restriction on whole-body averaged SAR under the same conditions varies from 128 V m^{-1} at 6 MHz to 37.5 V m^{-1} at 22 MHz. The ICNIRP public electric field reference levels are 35.5 V m^{-1} at 6 MHz, and 28.0 V m^{-1} for frequencies above 10 MHz.

Calculations for horizontally polarized electric fields have been included in this work as it is the predominant field orientation from the antennas used by BBC World Service in this frequency range. When the field was horizontally polarized, the electric field values required to produce the ICNIRP basic restrictions were significantly above reference levels. In the arms out horizontally to the side posture, the strongest coupling condition for horizontal polarization, calculated values required to produce occupational restrictions on whole-body averaged SAR varied from 917 V m^{-1} at 6 MHz to 271 V m^{-1} at 22 MHz. The calculated electric field values required to produce the ICNIRP public restriction on whole-body averaged SAR varied from 410 V m^{-1} at 6 MHz to 121 V m^{-1} at 22 MHz, over four times higher than the ICNIRP reference level of 28.0 V m^{-1}. For a horizontally polarized electric field with the arms held out horizontally at the frequencies studied, the localised SAR in the arm is marginally more restrictive than the whole-body SAR. For example, at 22 MHz, an electric field of 260 V m^{-1} is required to produce the ICNIRP occupational restriction on limb SAR. As already stated above, a field value of 271 V m^{-1} is required to produce the whole-body SAR restriction level at this frequency.

The localised SAR in the leg is the most restrictive quantity at the frequencies studied when the incident electric field is vertically polarized. At 22 MHz for the barefoot model under grounded conditions, electric field values required to produce basic restrictions are below the ICNIRP electric field strength reference levels. However, the ICNIRP reference levels on limb currents are 100 mA for occupational and 45 mA for public exposure between 10 MHz and 110 MHz. As an example, at 22 MHz the electric field value required for the basic public restriction of 4 W kg^{-1} averaged over 10 g in the leg is 26.1 V m^{-1} when the model is barefoot on a ground plane. The corresponding external electric field value for a limb current of 45 mA is 16.9 V m^{-1}, hence the limb current reference levels would provide compliance with basic restrictions on localised SAR averaged over 10 g in the leg.

Calculations of SAR in NORMAN have also been compared with induced current density values. These calculations clearly indicate that SAR is the more restrictive quantity at the frequencies studied in this work.

Text continues on page 26 ...

Table 5.1
Calculated whole-body averaged SAR for the plane wave exposure of NORMAN in the standard, arms vertically to the side and arms out horizontally postures. The incident electric field is 1 V m^{-1} (rms) and either vertically or horizontally polarized.

Frequency (MHz)	Whole-body averaged SAR (μW kg^{-1})				
	Vertically polarized E field			Horizontally polarized E field	
	Isolated	With shoes	Grounded	Isolated	Isolated (arms out)
6	0.536	2.83	4.89	0.113	0.476
8	0.785	4.44	7.76	0.135	0.748
11	1.43	8.54	14.9	0.180	1.40
13	2.02	12.4	21.6	0.221	1.90
16	3.16	18.2	31.5	0.303	2.80
19	4.80	25.6	43.3	0.411	3.99
22	6.99	35.6	56.9	0.544	5.45

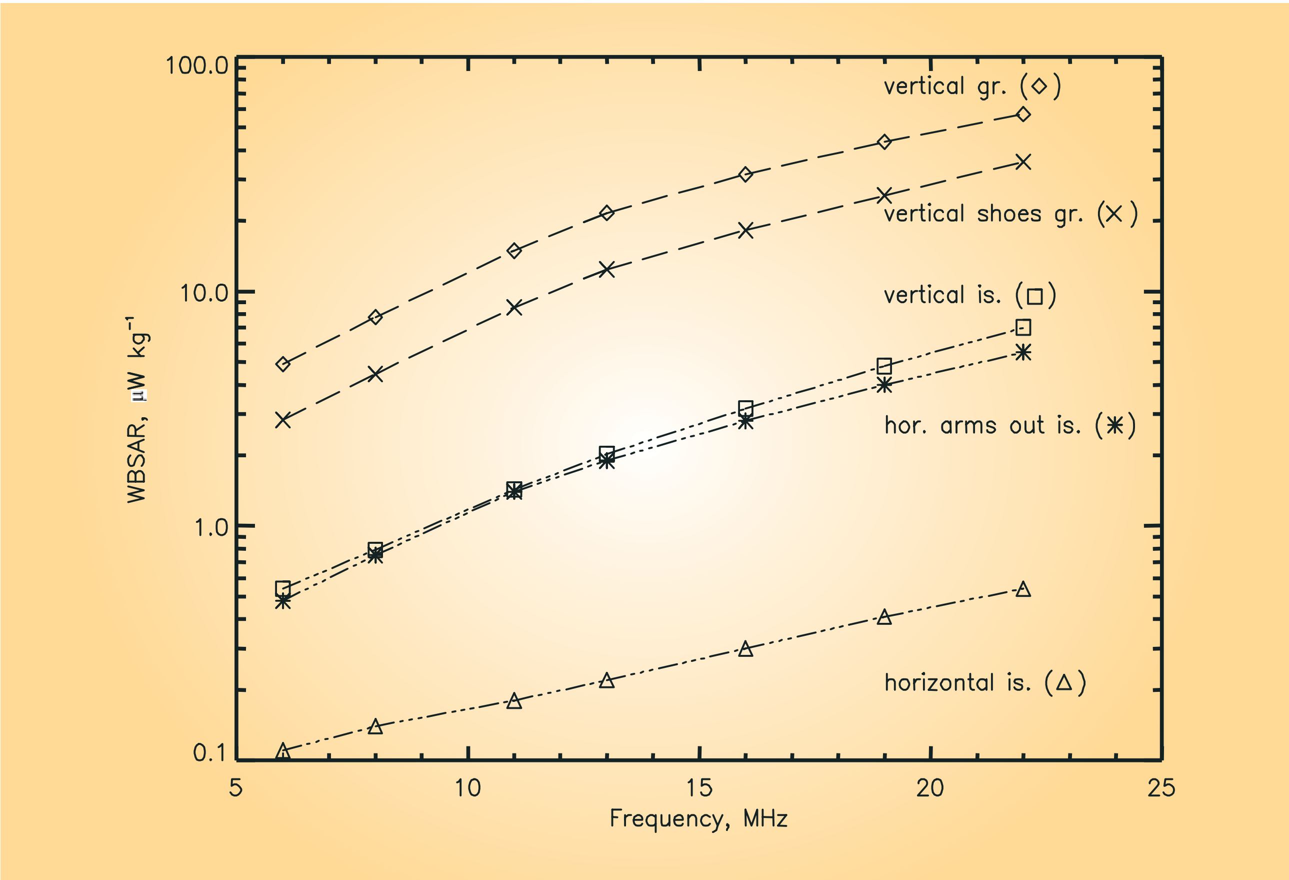

Figure 5.1
Calculated whole-body averaged SAR values. These are for vertically and horizontally polarized fields in the standard and arms horizontally out to the side posture under isolated, shod and grounded conditions. The incident electric field is 1 V m^{-1} (rms).

Table 5.2
Calculated ankle current for the plane wave exposure of NORMAN in the standard, arms vertically to the side and arms out horizontally postures. The incident electric field is 1 V m^{-1} (rms) and either vertically or horizontally polarized.

Frequency (MHz)	Ankle current (mA)				
	Vertically polarized E field			Horizontally polarized E field	
	Isolated	With shoes	Grounded	Isolated	Isolated (arms out)
6	0.195	0.523	0.726	0.054	0.066
8	0.228	0.671	0.933	0.055	0.067
11	0.291	0.938	1.30	0.054	0.066
13	0.339	1.13	1.58	0.054	0.066
16	0.423	1.40	1.94	0.057	0.079
19	0.530	1.68	2.31	0.064	0.092
22	0.648	1.98	2.66	0.072	0.099

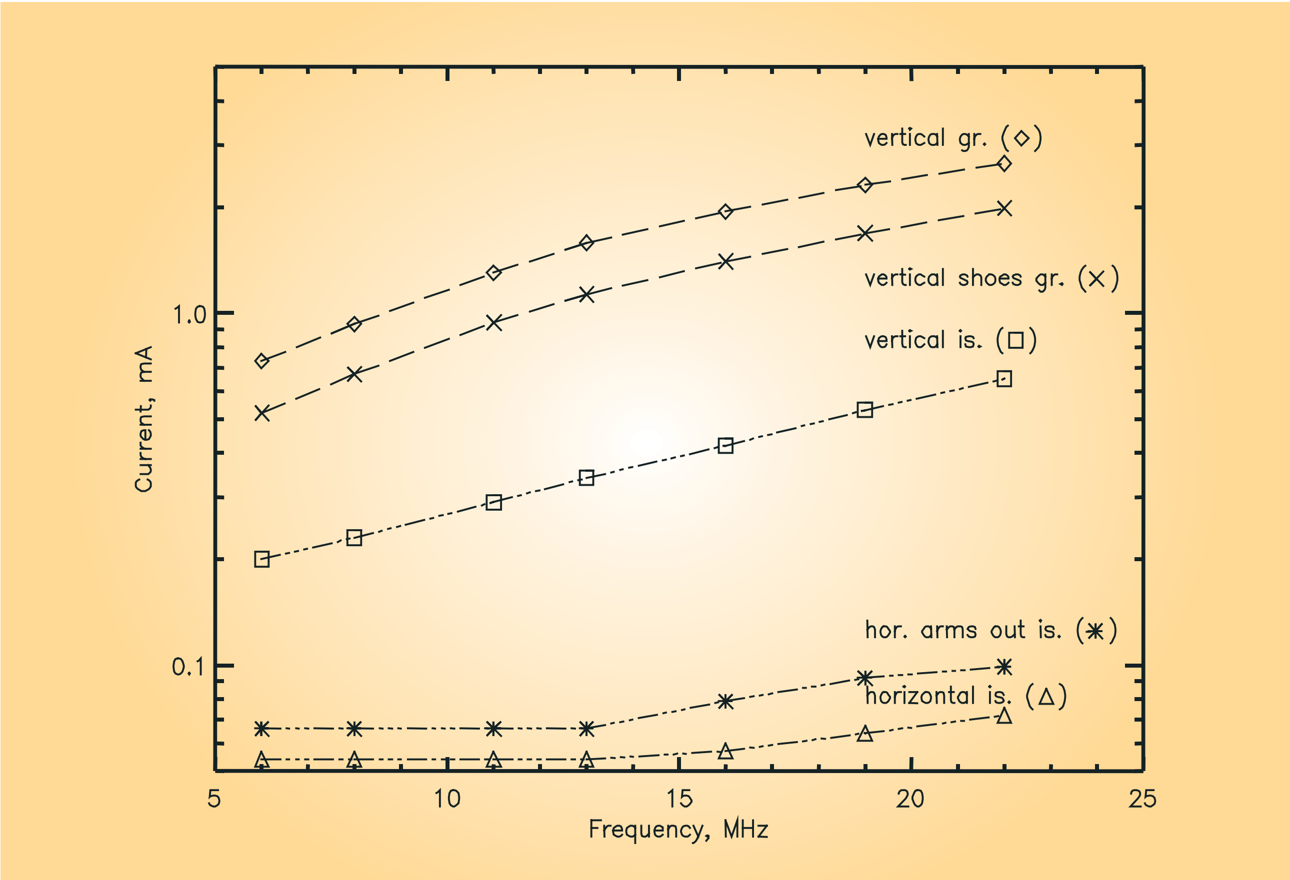

Figure 5.2
Calculated ankle current values. These are for vertically and horizontally polarized fields in the standard and arms horizontally out to the side posture under isolated, shod and grounded conditions. The incident electric field is 1 V m^{-1} (rms).

Table 5.3
Comparison of ICNIRP occupational reference levels with calculated electric field values required to produce basic restrictions on whole-body averaged SAR, for exposure of NORMAN in the standard, arms vertically to the side and arms out horizontally postures. The values are for vertically and horizontally polarized electric fields.

Frequency (MHz)	ICNIRP reference level (V m^{-1})	Electric field values (V m^{-1})				
		Vertically polarized E field			Horizontally polarized E field	
		Isolated	With shoes	Grounded	Isolated	Isolated (arms out)
6	101.7	863	376	286	1880	917
8	76.3	714	300	227	1720	731
11	61	529	216	164	1490	535
13	61	445	180	136	1350	459
16	61	356	148	113	1150	378
19	61	289	125	96.1	987	317
22	61	239	106	83.8	858	271

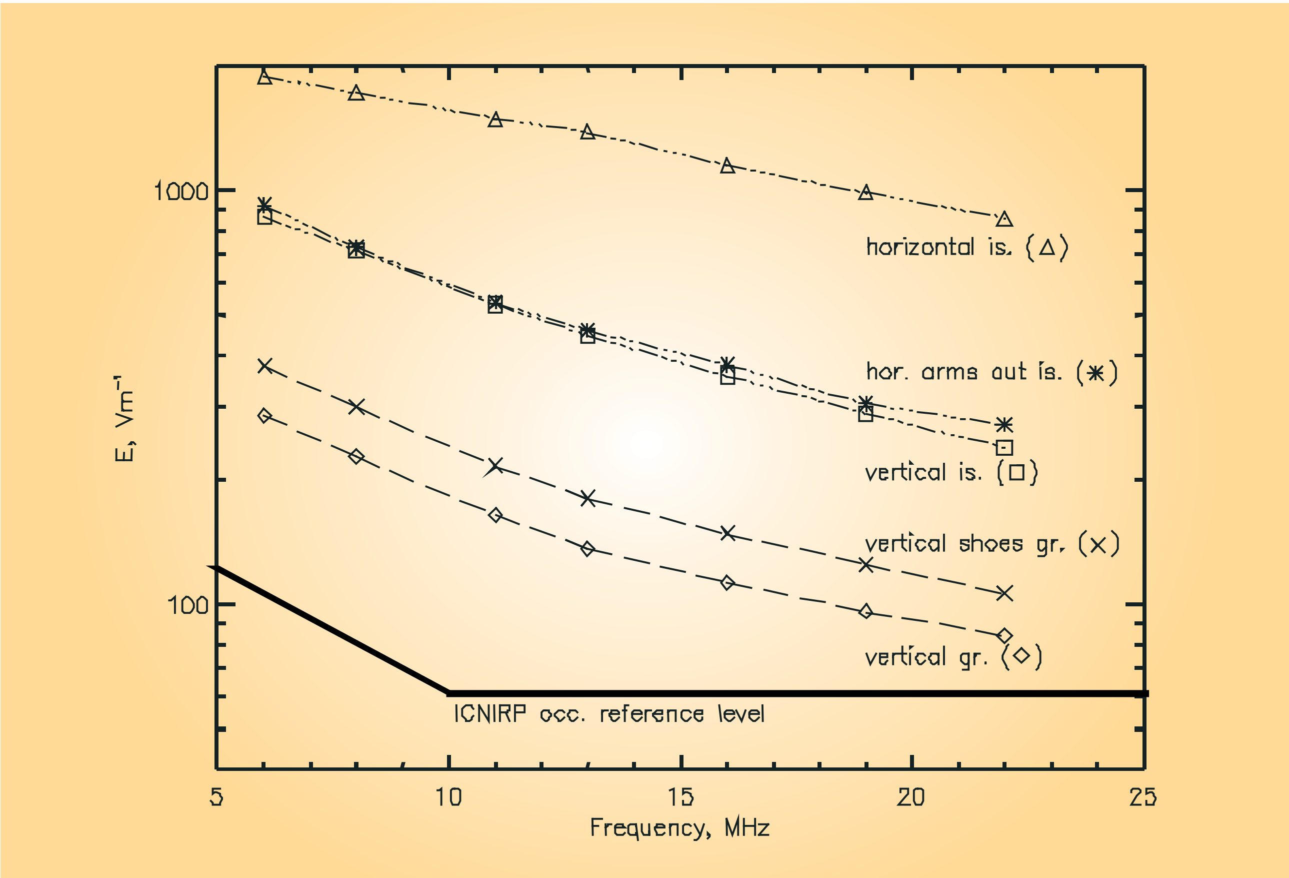

Figure 5.3
Comparison of ICNIRP occupational reference levels with calculated electric field values required to produce basic restrictions on whole-body averaged SAR. These are for vertically and horizontally polarized fields in the standard and arms horizontally out to the side posture under isolated, shod and grounded conditions.

Table 5.4
Comparison of ICNIRP public reference levels with calculated electric field values required to basic restrictions on the whole-body averaged SAR, for the exposure of NORMAN in the standard, arms vertically to the side and arms out horizontally postures. The values are for vertically and horizontally polarized electric fields.

Frequency (MHz)	ICNIRP reference levels (V m^{-1})	Electric field values (V m^{-1})				
		Vertically polarized E field			Horizontally polarized E field	
		Isolated	With shoes	Grounded	Isolated	Isolated (arms out)
6	35.5	386	168	128	841	410
8	30.8	319	134	102	770	327
11	28	237	96.8	73.3	667	239
13	28	199	80.3	60.9	602	205
16	28	159	66.3	50.4	514	169
19	28	129	55.9	43.0	441	142
22	28	107	47.4	37.5	384	121

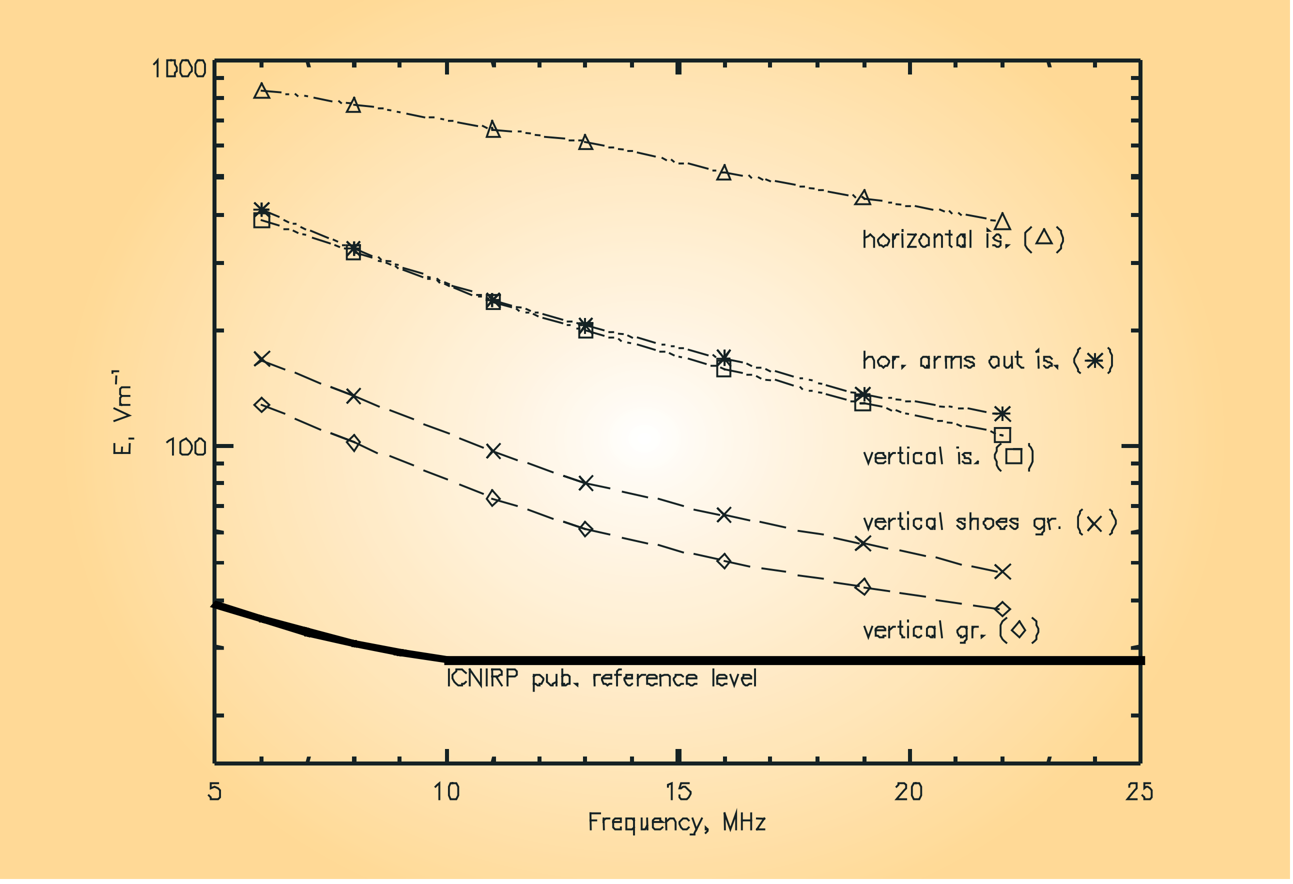

Figure 5.4
Comparison of ICNIRP public reference levels with calculated electric field values required to produce basic restrictions on whole-body averaged SAR. These are for plane wave vertically and horizontally polarized fields in the standard and arms horizontally out to the side posture under isolated, shod and grounded conditions.

Table 5.5
Comparison of ICNIRP occupational reference levels with calculated electric field values required to produce basic restrictions on leg SAR, for the exposure of NORMAN in the standard, arms vertically to the side and arms out horizontally postures. The values are for vertically and horizontally polarized electric fields.

Freq. (MHz)	SAR(10g) (W kg^{-1} per A)	ICNIRP reference level (V m^{-1})	Electric field values (V m^{-1})				
			Vertically polarized E field			Horizontally polarized E field	
			Isolated	With shoes	Grounded	Isolated	Isolated (arms out)
6	1030	101.7	715	266	192	2580	2110
8	1000	76.3	620	211	152	2570	2110
11	964	61	495	154	111	2670	2180
13	934	61	432	129	92.6	2710	2220
16	866	61	359	109	78.3	2670	1920
19	851	61	289	91.3	66.4	2400	1670
22	831	61	239	78.4	58.3	2160	1570

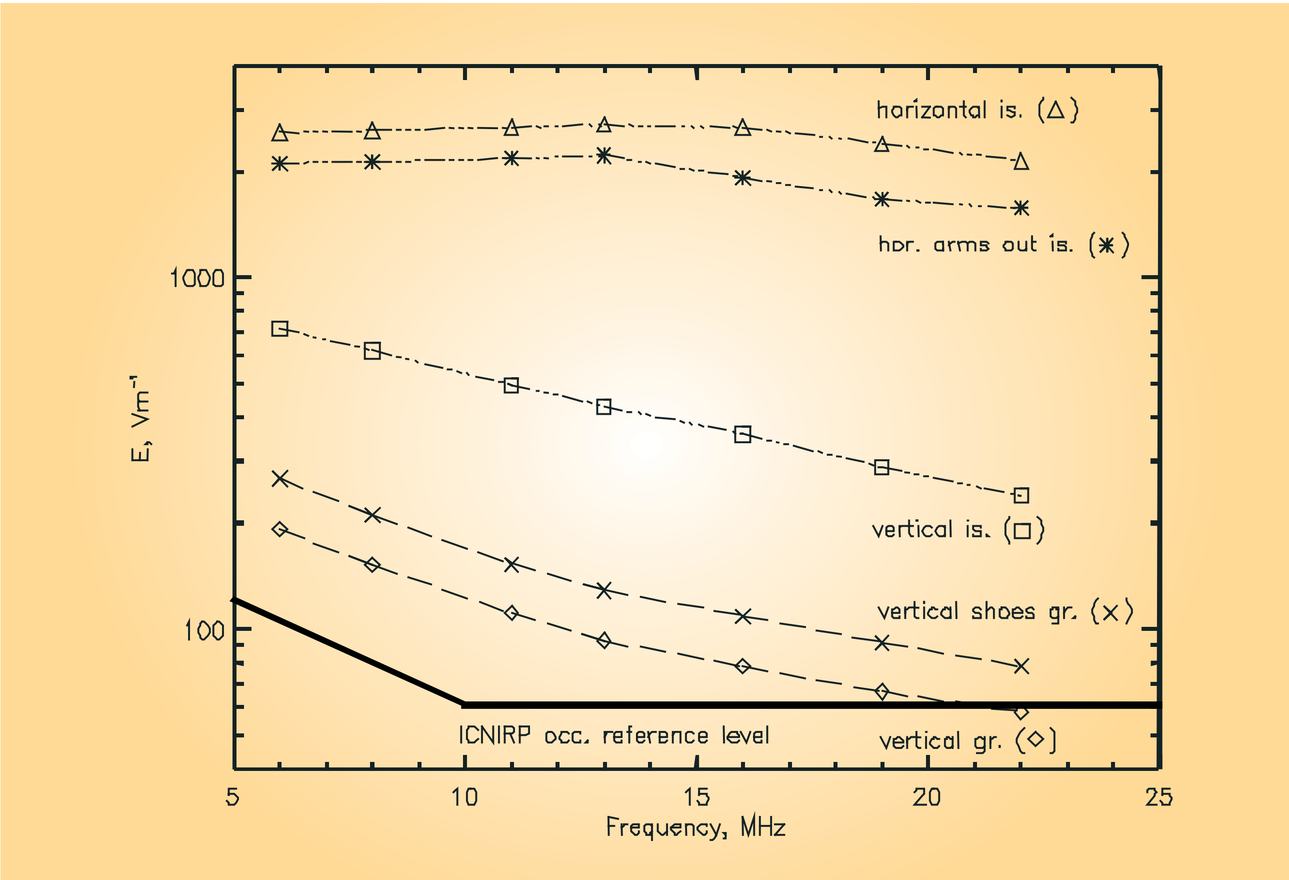

Figure 5.5
Comparison of ICNIRP occupational reference levels with calculated electric field values required to produce basic restrictions on leg SAR. These are for vertically and horizontally polarized fields in the standard and arms horizontally out to the side posture under isolated, shod and grounded conditions.

Table 5.6
Comparison of ICNIRP public reference levels with calculated electric field values required to produce basic restrictions on leg SAR, for the exposure of NORMAN in the standard, arms vertically to the side and arms out horizontally postures. The values are for vertically and horizontally polarized electric fields.

Freq. (MHz)	SAR(10g) (W kg^{-1} per A)	ICNIRP reference level (V m^{-1})	Electric field values (V m^{-1})				
			Vertically polarized E field			Horizontally polarized E field	
			Isolated	With shoes	Grounded	Isolated	Isolated (arms out)
6	1030	35.5	320	119	85.8	1150	944
8	1000	30.8	277	94.3	67.8	1150	944
11	964	28	221	68.7	49.6	1190	976
13	934	28	193	57.9	41.4	1210	992
16	866	28	161	48.5	35.0	1190	860
19	851	28	129	40.8	29.7	1070	745
22	831	28	107	35.0	26.1	964	701

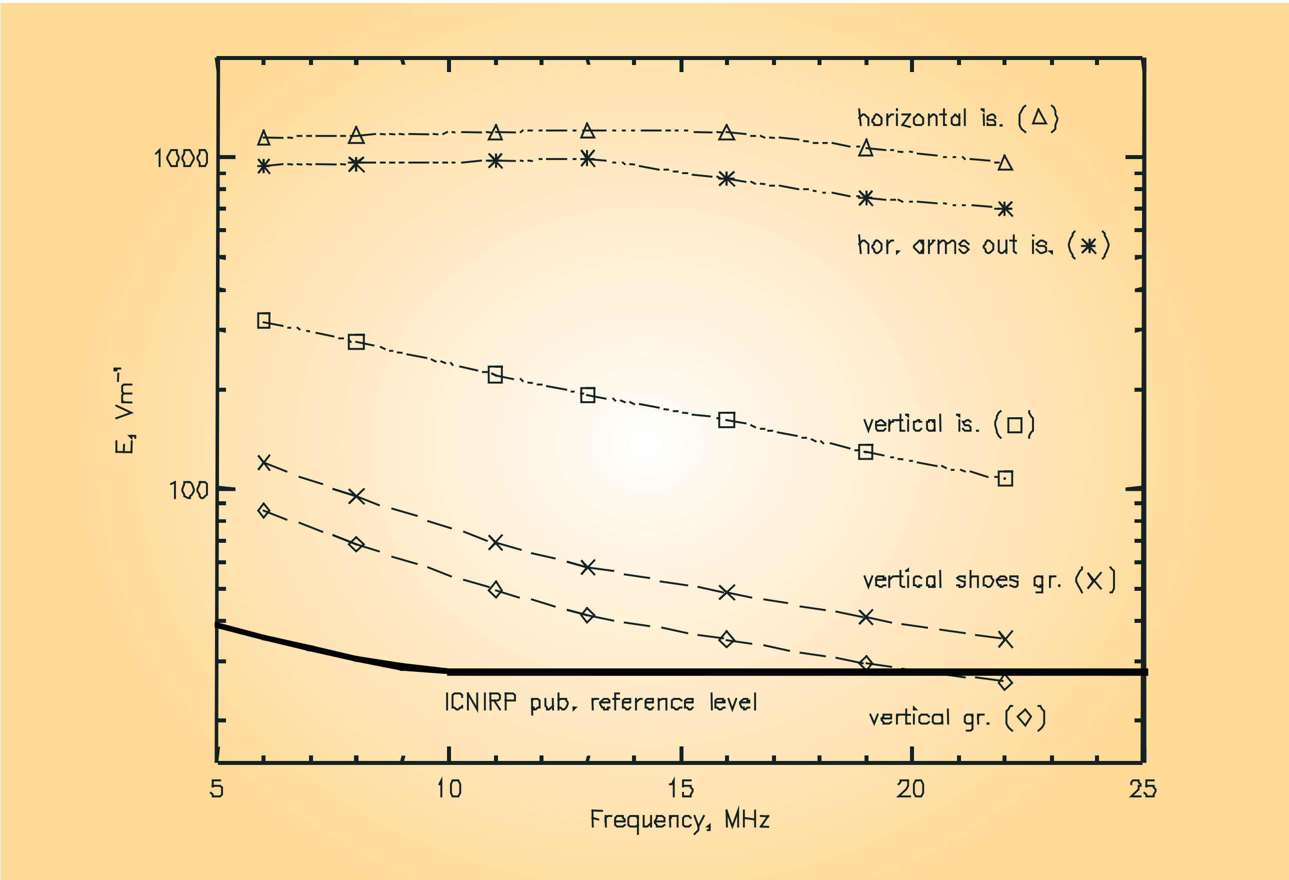

Figure 5.6
Comparison of ICNIRP public reference levels with calculated electric field values required to produce basic restrictions on leg SAR. These are for plane wave vertically and horizontally polarized fields in the standard and arms horizontally out to the side posture under isolated, shod and grounded conditions.

Table 5.7
Calculated wrist current for the plane wave exposure of NORMAN in the standard, arms vertically to the side and arms out horizontally postures. The incident electric field is 1 V m^{-1} (rms) and either vertically or horizontally polarized.

Frequency (MHz)	Wrist current (mA)				
	Vertically polarized E field			Horizontally polarized E field	
	Isolated	With shoes	Grounded	Isolated	Isolated (arms out)
6	0.010	0.033	0.043	0.031	0.178
8	0.011	0.041	0.062	0.037	0.219
11	0.020	0.052	0.084	0.046	0.282
13	0.025	0.062	0.100	0.052	0.317
16	0.034	0.090	0.133	0.062	0.379
19	0.047	0.120	0.167	0.072	0.451
22	0.062	0.139	0.185	0.082	0.525

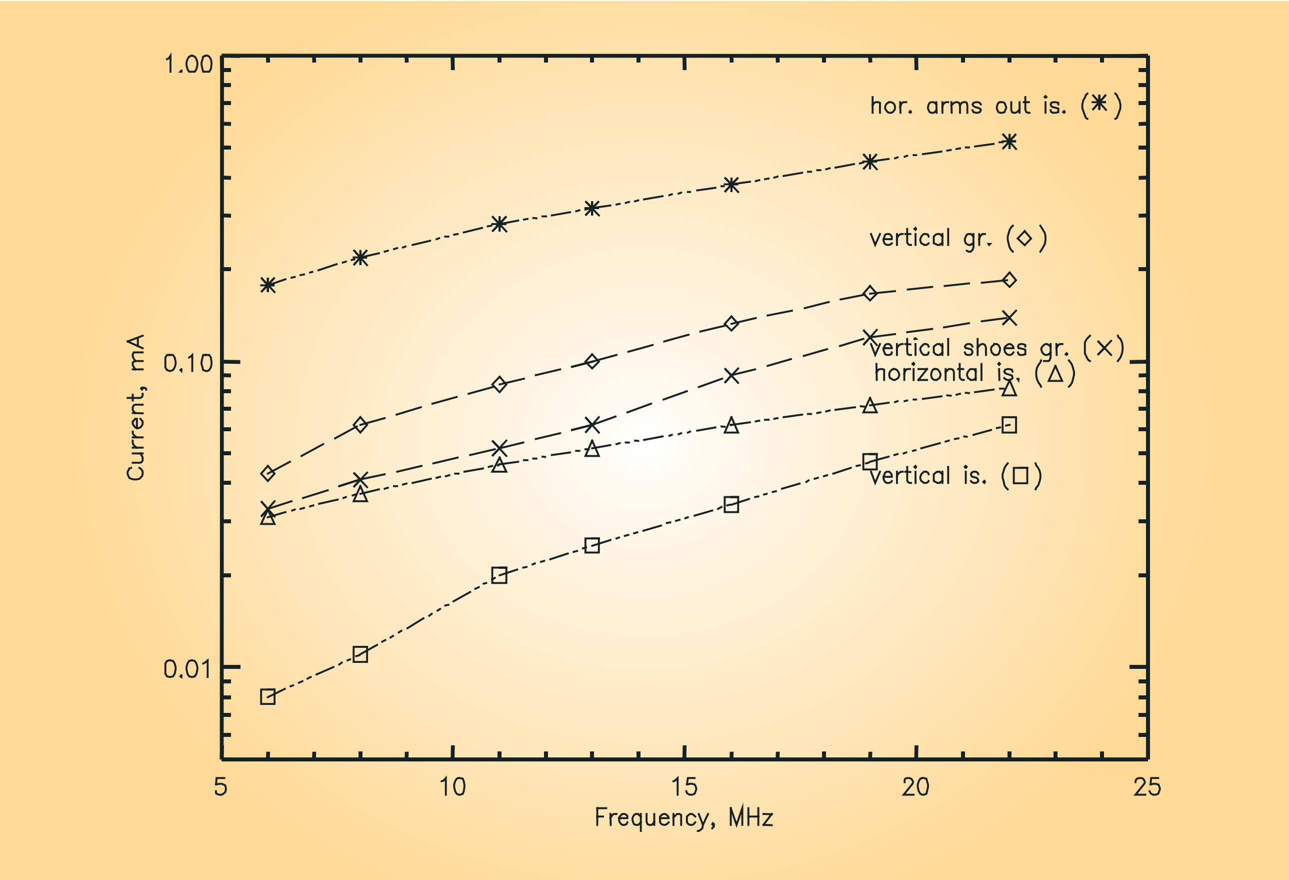

Figure 5.7
Calculated wrist current values. These are for vertically and horizontally polarized fields in the standard and arms horizontally out to the side posture under isolated, shod and grounded conditions. The incident electric field is 1 V m^{-1} (rms).

Table 5.8
Comparison of ICNIRP occupational reference levels with calculated electric field values required to produce basic restrictions on arm SAR, for the exposure of NORMAN in the standard, arms vertically to the side and arms out horizontally postures. The values are for vertically and horizontally polarized electric fields.

Freq. (MHz)	SAR(10g) (W kg^{-1} per A)	ICNIRP reference level (V m^{-1})	Electric field values (V m^{-1})				
			Vertically polarized E field			Horizontally polarized E field	
			Isolated	With shoes	Grounded	Isolated	Isolated (arms out)
6	1340	101.7	12216.9	3700	2840	3940	686
8	1310	76.3	11232.8	3010	1990	3340	564
11	1250	61	6324.6	2430	1510	2750	449
13	1180	61	5207.6	2100	1300	2500	410
16	1120	61	3930.3	1480	1000	2160	353
19	1090	61	2882.1	1130	811	1880	300
22	1070	61	2205.1	984	739	1670	260

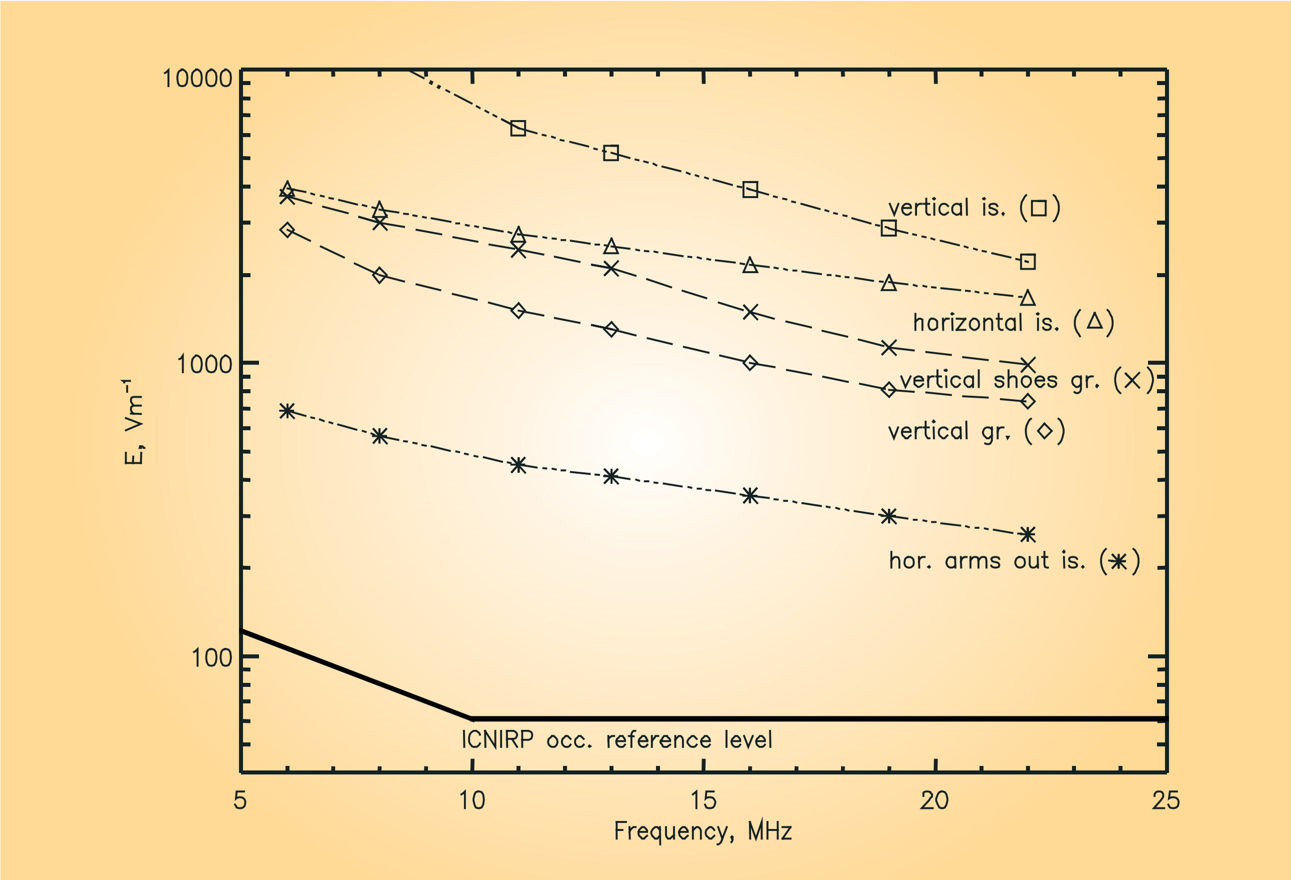

Figure 5.8
Comparison of ICNIRP occupational reference levels with calculated electric field values required to produce basic restrictions on arm SAR. These are for vertically and horizontally polarized fields in the standard and arms horizontally out to the side posture under isolated, shod and grounded conditions.

Table 5.9
Comparison of ICNIRP public reference levels with calculated electric field values required to produce basic restrictions on arm SAR, for the exposure of NORMAN in the standard, arms vertically to the side and arms out horizontally postures. The values are for vertically and horizontally polarized electric fields.

Freq. (MHz)	SAR(10g) (W kg^{-1} per A)	ICNIRP reference level (V m^{-1})	Electric field values (V m^{-1})				
			Vertically polarized E field			Horizontally polarized E field	
			Isolated	With shoes	Grounded	Isolated	Isolated (arms out)
6	1340	35.5	5460	1660	1270	1762	307
8	1310	30.8	5020	1350	891	1494	252
11	1250	28	2830	1090	673	1230	201
13	1180	28	2330	939	582	1120	184
16	1120	28	1760	664	449	964	158
19	1090	28	1290	505	363	841	134
22	1070	28	986	440	331	746	116

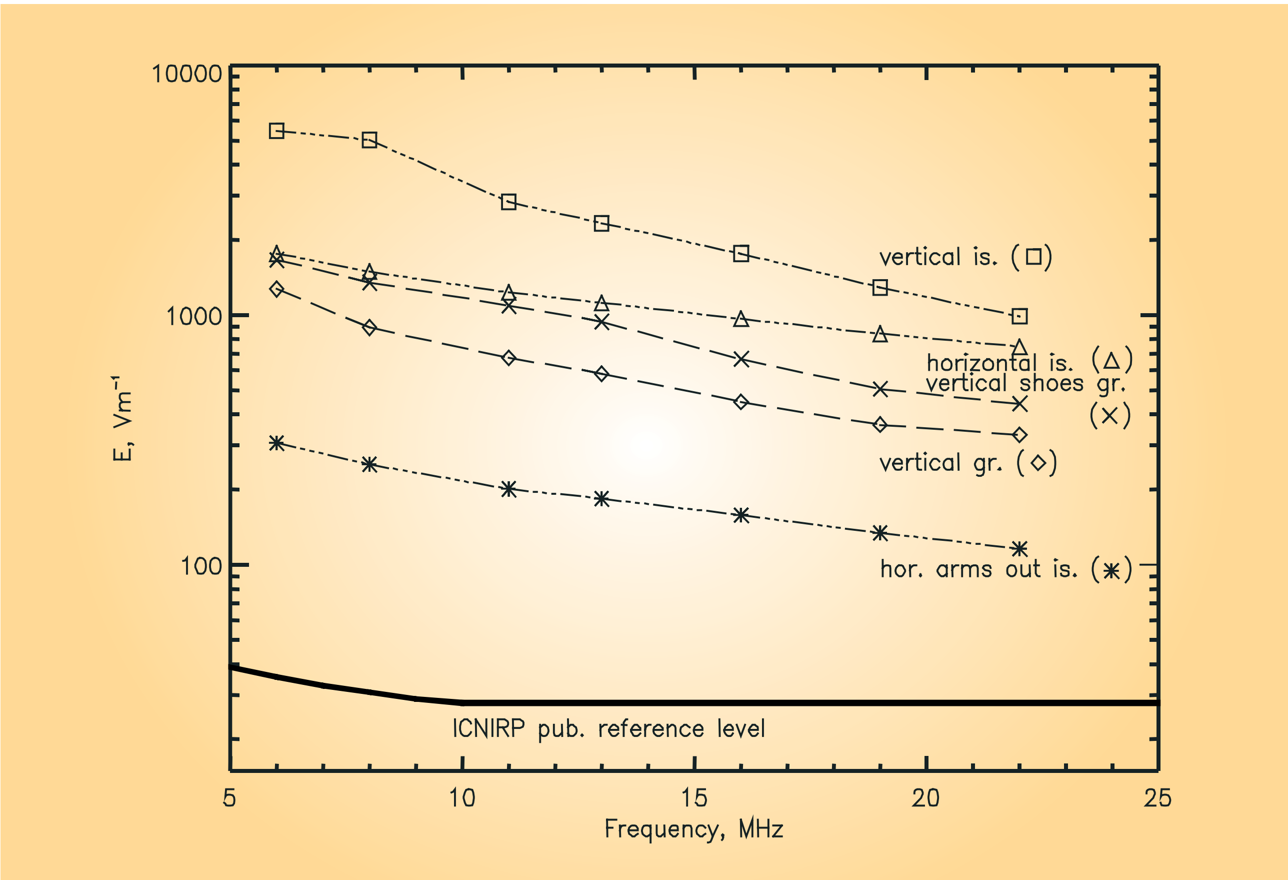

Figure 5.9
Figure 5. 9 Comparison of ICNIRP public reference levels with calculated electric field values required to produce basic restrictions on arm SAR. These are for plane wave vertically and horizontally polarized fields in the standard and arms horizontally out to the side posture under isolated, shod and grounded conditions.

Table 5.10
Comparison of ICNIRP occupational limb current reference levels with calculated ankle currents required to produce basic restrictions on leg SAR (20 W kg^{-1}).

Frequency (MHz)	ICNIRP reference level (mA)	Ankle current value (mA)
6	-	139
8	-	141
11	100	144
13	100	146
16	100	152
19	100	153
22	100	155

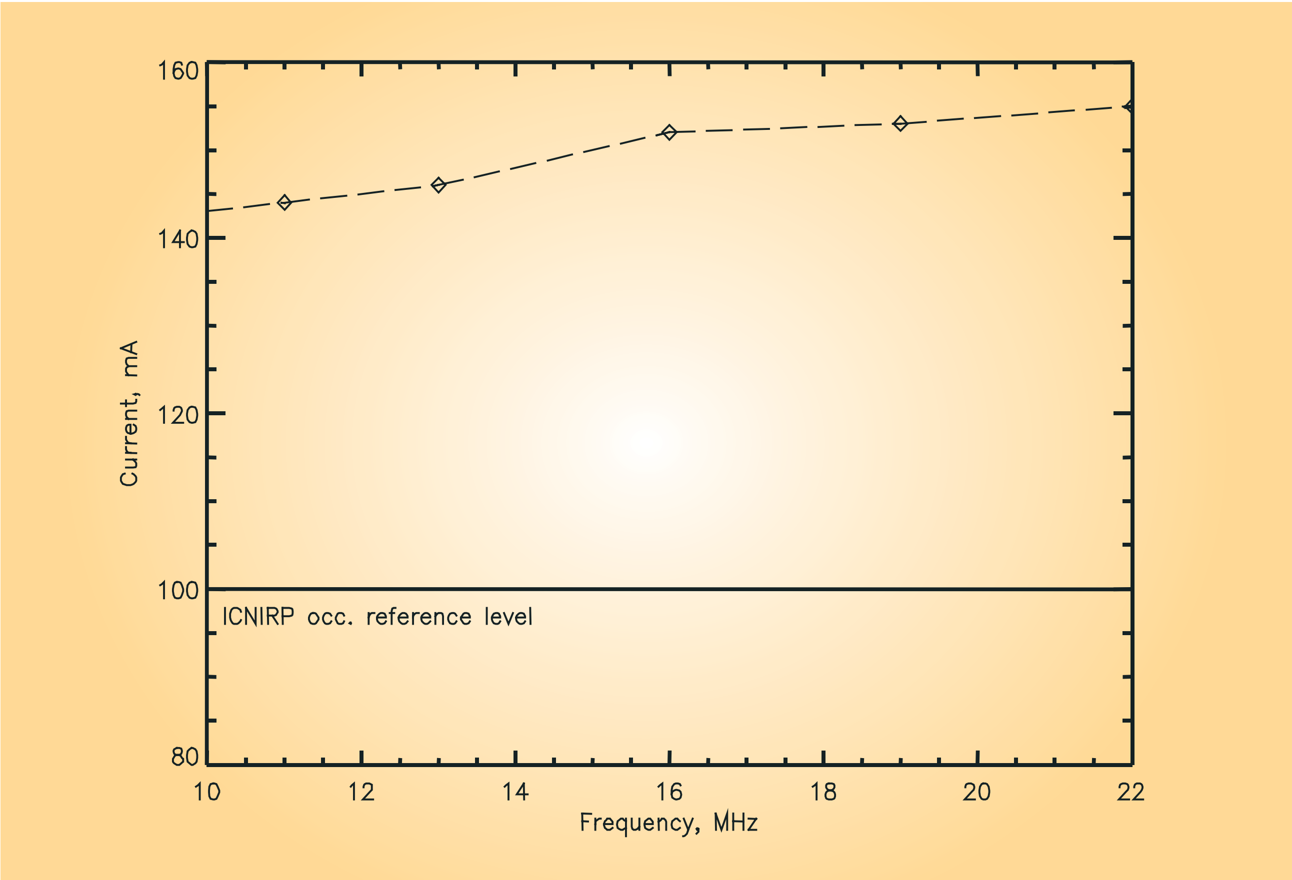

Figure 5.10
Comparison of ICNIRP occupational limb current reference levels with calculated ankle current required to produce the basic restrictions on leg SAR.

Table 5.11
Comparison of ICNIRP public limb current reference levels with calculated ankle currents required to produce basic restrictions on leg SAR (4 W kg^{-1}).

Frequency (MHz)	ICNIRP reference level (mA)	Ankle current value (mA)
6	-	62.4
8	-	63.1
11	45	64.4
13	45	65.3
16	45	68.0
19	45	68.4
22	45	69.3

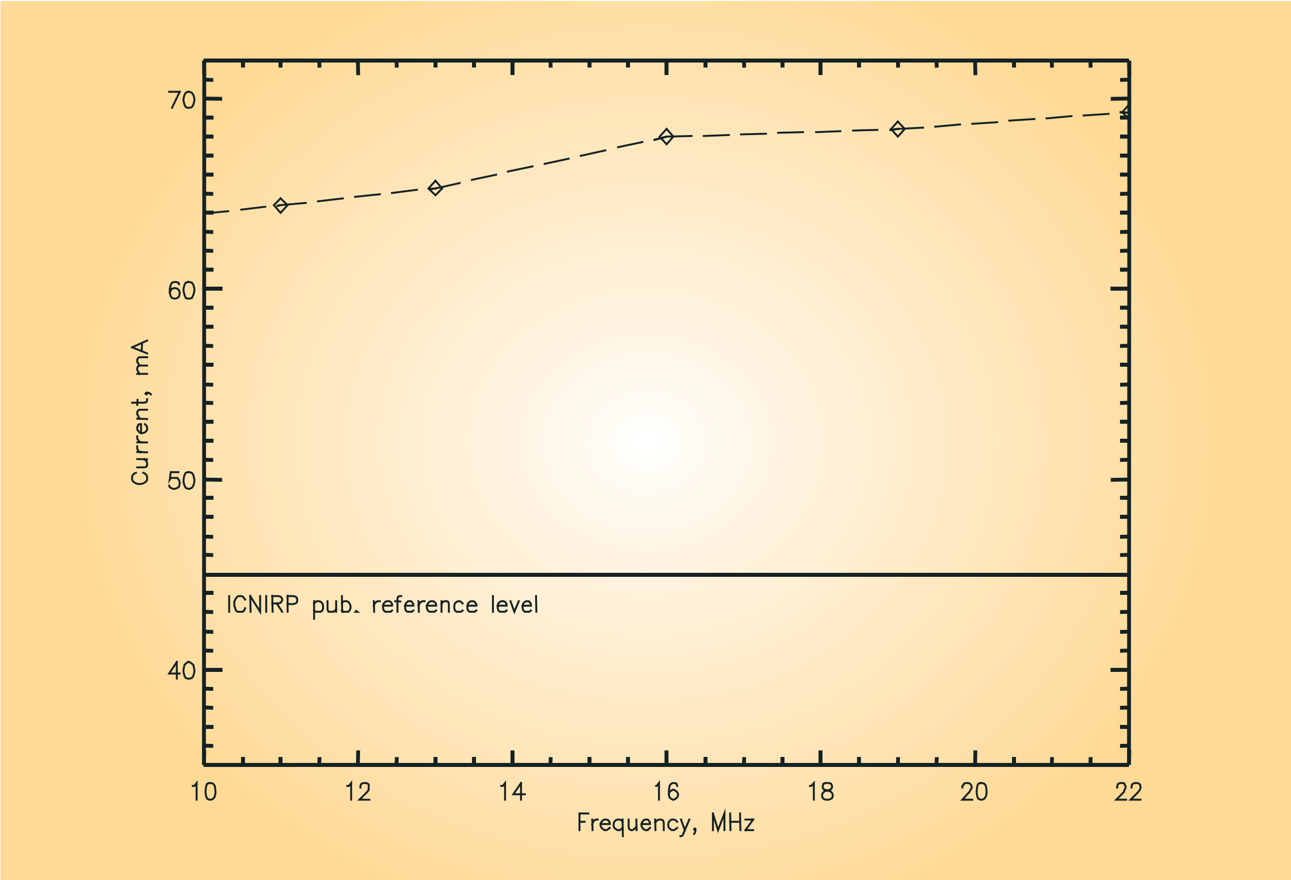

Figure 5.11
Comparison of ICNIRP public limb current reference levels with calculated ankle current required to produce the basic restrictions on leg SAR.

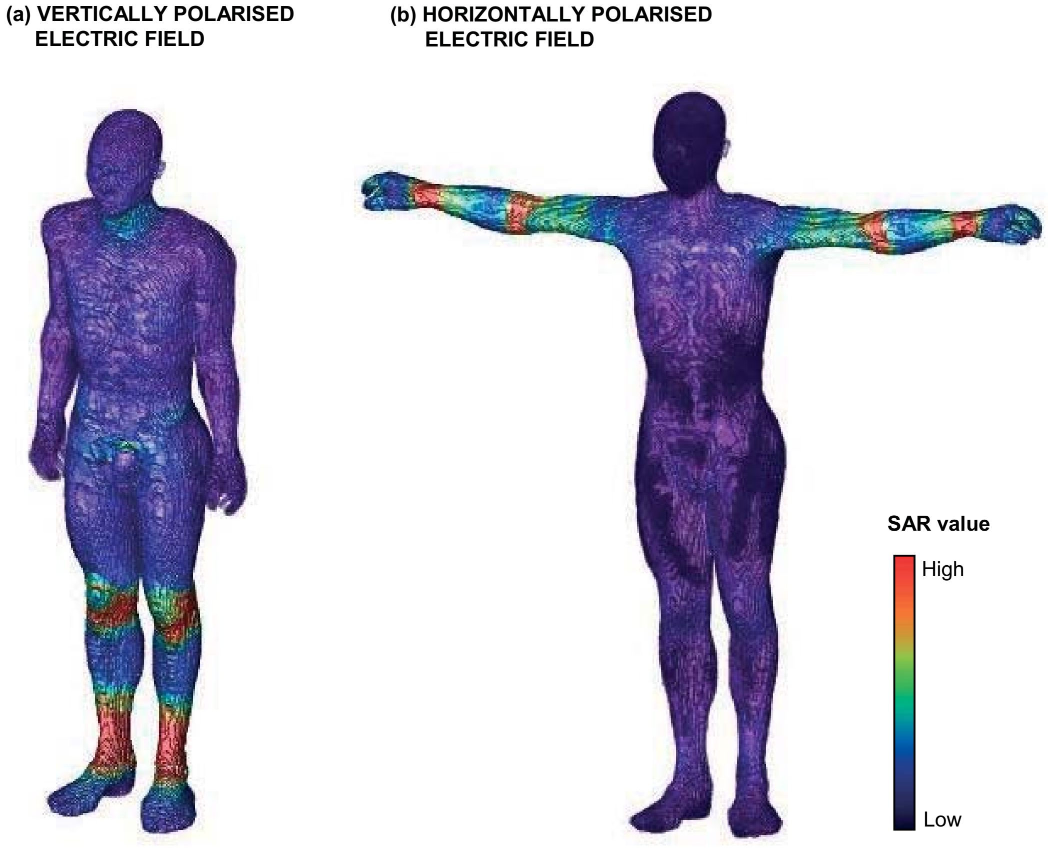

Figure 5.12
SAR in each 4 mm voxel of the numerical model for the two postures at 22 MHz for (a) vertically and (b) horizontally polarized electric fields under isolated conditions. The colour map is a rainbow spectrum which has been stretched to enhance the lower end. It is only intended to give a general view of absorption regions within the body.

Table 5.12
Calculated electric field values, V m^{-1} (rms), required to produce ICNIRP occupational and public (in brackets) restrictions on whole-body averaged SAR, SAR in the leg averaged over 10 g, and current density averaged over 1 cm^2, for the plane wave vertically polarized field exposure of NORMAN in the standard, arms vertically to the side posture under grounded conditions.

Frequency (MHz)	Whole body SAR Electric field values (V m^{-1})	Leg SAR Electric field values (V m^{-1})	Current density Electric field values (V m^{-1})
1	1250 (557)	835 (373)	2700 (540)
10	183 (82)	122 (54.8)	2160 (432)

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