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THE RELATIONSHIP BETWEEN ANATOMICALLY CORRECT ELECTRIC AND MAGNETIC FIELD DOSIMETRY AND PUBLISHED ELECTRIC AND MAGNETIC FIELD EXPOSURE LIMITS

Robert Kavet[1,*], Thanh Dovan[2] and J. Patrick Reilly[3]
[1]Electric Power Research Institute, 3420 Hillview Avenue, Palo Alto, CA 94304, USA
[2]SP AusNet, 2 Southbank Blvd., Southbank, VIC 3006, Australia
[3]Metatec Associates, 12516 Davan Drive, Silver Spring, MD 20904

*Corresponding author: rkavet@epri.com

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Electric and magnetic field exposure limits published by International Commission for Non-Ionizing Radiation Protection and Institute of Electrical and Electronics Engineers are aimed at protection against adverse electrostimulation, which may occur by direct coupling to excitable tissue and, in the case of electric fields, through indirect means associated with surface charge effects (e.g. hair vibration, skin sensations), spark discharge and contact current. For direct coupling, the basic restriction (BR) specifies the not-to-be-exceeded induced electric field. The key results of anatomically based electric and magnetic field dosimetry studies and the relevant characteristics of excitable tissue were first identified. This permitted us to assess the electric and magnetic field exposure levels that induce dose in tissue equal to the basic restrictions, and the relationships of those exposure levels to the limits now in effect. We identify scenarios in which direct coupling of electric fields to peripheral nerve could be a determining factor for electric field limits.

INTRODUCTION

Limits for exposure to electric fields, magnetic fields and contact currents, as published by the International Commission for Non-Ionizing Radiation Protection (ICNIRP) and the Institute of Electrical and Electronics Engineers (IEEE) are structured to protect against potentially adverse effects resulting from electrostimulation at frequencies less than 100 kHz[1, 2]. [IEEE's existing standard for extremely-low frequency (ELF) fields extends up to 3 kHz, with frequencies to 100 kHz covered in IEEE's radiofrequency (RF) standard[3].] Both organisations define electrostimulation identically as "[i]nduction of a propagating action potential in excitable tissue by an applied electrical stimulus; electrical polarization of presynaptic processes leading to a change in post synaptic cell activity." The interactions comprised by this definition may include potentially annoying, aversive or painful surface charge effects (e.g., hair vibration, skin sensations), spark discharge and contact currents associated with environmental electric fields, and potentially adverse neural and/or synaptic stimulation resulting from electric fields coupled directly into the body by external electric and magnetic fields. Contact currents may also occur from physically bridging a potential difference in the absence of an apparent source of an electric field such as a high voltage transmission line. Both organisations also publish limits for frequencies greater than 100 kHz that address electrostimulation (ICNIRP to 10 MHz; IEEE to 5 MHz). These apply to circumstances (low duty cycle RF) in which the electrostimulation threshold would be the exposure-limiting factor, rather than tissue heating[3, 4]. [Note: The IEEE Standard is sponsored by the IEEE International Committee on Electromagnetic Safety (Standards Coordinating Committee 28) on Non-Ionizing Radiation (abbreviated to ICES). IEEE will be used to identify the standard throughout the paper.]

ICNIRP and IEEE refer to their exposure limit documents, respectively, as a *Guideline* and a *Standard*. When discussed collectively here, they will be referred to simply as 'exposure limits'. Both the organisations specify not-to-be-exceeded electric fields in tissue, or 'basic restrictions' (BR), as well as limits to environmental fields, which assure that the BR is not exceeded; in this paper, these environmental fields are referred to as 'Exposure Reference Levels' (ERL). In their current terminology ICNIRP uses 'Reference Level' and IEEE uses 'Maximum Permissible Exposure', which define limits to environmental electric and magnetic field exposures. Both ICNIRP and IEEE exposure limits designate BRs and ERLs for two populations. One, referred to as the 'Lower Tier', consists of members of the general public who have more restrictive limits to account for their presumed lack

of awareness of electromagnetic environments and associated safety practices. The other, the 'Upper Tier', with comparatively less restrictive limits, comprises individuals who, through either occupation or other training, are aware of electromagnetic environments and the potential associated effects; in addition, these individuals are cognizant of mitigation or avoidance practices when they become necessary.

Over the past 15–20 y, there have been significant advances in the use of anatomically correct, high-resolution models of humans to compute current densities and electric fields coupled into the body's tissues from environmental electric and magnetic fields. Reliability of the validity of the computed quantities has been enhanced as evidenced by inter-laboratory agreement across a variety of anatomical dose models[5, 6]. For example, laboratories at the University of Victoria (British Columbia, Canada) and the National Radiological Protection Board (NRPB, UK, now the Health Protection Agency) conducted a comparison between the results of their respective anatomical modelling of an adult exposed to a 60-Hz magnetic field front-to-back[5]. Both the laboratories used the scalar potential finite difference method. In two analyses (hands at side, 27 tissue sites; hands in front, 29 tissue sites), there was no more than a 2 % discrepancy on average, 99th percentile and maximum electric field in any tissue. A comparison was conducted among six laboratories in Japan analysing a standard Japanese adult model exposed to a 50-Hz magnetic field (TARO)[6]. Although not all used the same computational method, the investigators reported consistent results among five of the six. For example, for front-to-back exposure the maximum electric field within the body was in the skin for five of the laboratories (and in cortical bone for the sixth), with a total range across the five of less than 25 % of their mean value. Considering the potential instability of the maximum tissue field due to staircasing errors, the study added to the reliability of anatomically correct dosimetry. Furthermore, more recent analyses indicate that the 99th percentile electric field within a particular tissue site is preferred as an estimate of the maximum dose to that site, rather than the computed absolute maximum, which is often subject to artefact[7]. The ICNIRP Guideline published in 2010 relied on anatomically correct dosimetry to specify its ERLs for magnetic fields, whereas its predecessor used a simple loop model to estimate coupling into tissue from magnetic fields[4]. The IEEE Standard effective as of this writing uses a three-dimensional ellipsoidal induction model approximation of an adult-sized person, which has a closed form solution, to derive ERLs.

For both ICNIRP and IEEE, magnetic field ERLs protect against adverse electrostimulation that results from direct coupling of the environmental field to excitable tissues. Electric field ERLs are designed in such a way as to protect against potentially adverse indirect effects (annoyance implied by ICNIRP; pain in IEEE) of spark discharge, and contact currents for ungrounded persons, as well as to ensure that the BRs are not exceeded, as described also for magnetic fields. The ICNIRP guideline's rationale also includes protection against surface charge effects for the Lower Tier at frequencies $\leq$50 Hz.

This paper's objective is to apply anatomically based dosimetry results to assess the electric and magnetic field exposure levels that couple electric fields in tissue at the level of the BRs of both tiers, and the relationships of those levels to the ERLs now in effect by ICNIRP and IEEE. For electric fields, this paper thus addresses whether there are conditions under which direct coupling may supersede indirect effects, which currently serve as the principal basis for the electric field ERL. In all cases, these relationships in adult-sized models are examined using the 99th percentile electric field coupled to tissue as our measure of dose.

COUPLING OF MAGNETIC AND ELECTRIC FIELDS TO LIVING BODIES

Magnetic fields

An environmental magnetic field induces electrical potential within a specific tissue, T, in the body according to the general formula (note in the following discussion of coupling that the symbols, B and E refer to the magnitudes of vector quantities)

$$E_{\mathrm{BT}} = K_{\mathrm{BT}} \frac{\mathrm{d}B}{\mathrm{d}t}$$

where E_{BT} is the instantaneous electric field in tissue due to the magnetic field; and $\mathrm{d}B/\mathrm{d}t$ is the instantaneous time rate of change of the ambient magnetic field and K_{BT} is a constant specific to tissue.

Similarly, for an electric field exposure, E, the instantaneous electric field in tissue, $E_{\mathrm{ET}}$is

$$E_{\mathrm{ET}} = K_{\mathrm{ET}} \frac{\mathrm{d}E}{\mathrm{d}t}$$

where $\mathrm{d}E/\mathrm{d}t$ is the instantaneous time rate of change of the ambient electric field and K_{ET} is a constant specific to tissue.

As the dose metric most relevant to electrostimulation is the electric field in tissue, current density will not be dealt with explicitly. However, when tissue-specific dosimetry data are available only in terms of current density, the electric field in tissue

can be estimated as

$$E_T = \frac{J_T}{\sigma_T}$$

where J_T is the current density in tissue (A/m^2) and σ_T is the tissue's conductivity (S/m).

For an ambient sinusoidal magnetic field, B,

$$E_{BT} = K_{BT} \times 2\pi f B \text{ and}$$

For an ambient sinusoidal electric field, E,

$$E_{ET} = K_{ET} \times 2\pi f E$$

Thus, for a sinusoidal field a coupling coefficient can be defined as the induced electric field in tissue, T, per unit magnetic (electric) field per Hz, as follows $C_{BT} = 2\pi K_{BT}$ expressed in units of V/m/(Tesla − Hz) and

$C_{ET} = 2\pi K_{ET}$ expressed in units of

$$\left(\frac{(\text{V m}^{-1})_{\text{in situ}}}{(\text{kV m}^{-1})_{\text{environmental}} - \text{Hz}}\right)$$

(subscripts for V m^{-1} and kV m^{-1} to distinguish external from internal electric fields).

For the xxth percentile dose in tissue, the parameters are notated accordingly, as follows:

$$C_{BTXX} = 2\pi K_{BTXX} \text{ and } C_{ETXX} = 2\pi K_{ETXX}$$

The IEEE Standard defined coupling between a magnetic field and the induced electric field using an ellipsoidal model with adult human dimensions, and a closed form linear transfer function that relates E_T at any point within the ellipsoid to dB/dt. Thus, appropriately sized ellipsoids and corresponding loci were selected for estimating the relationship of E_T to dB/dt. With estimates of the tissue-specific rheobase based on published values and the corresponding tissue time constant (for reference, both terms are defined below in Table 3), ERLs that corresponded to the BRs could be calculated with the following formula as written in the IEEE Standard

$$E_T = -\dot{B}_w \left| \frac{a^2 u \mathbf{a}_v - b^2 v \mathbf{a}_u}{a^2 + b^2} \right|$$

where quoting from the Standard, '$\mathbf{a}_u$ and $\mathbf{a}_v$ are unit vectors along the minor and major axes, respectively, (a, b) are the semi-major and semi-minor axes, respectively, (u, v) is the location within the exposed area, and $\dot{B}_w$ is the time rate of change of the magnetic field in a direction perpendicular to the cross section... The coordinate system is such that the minor axis of the ellipse is along the u-direction, and the major axis is along the v-direction'.

Since for a sinusoidal exposure, $E_T = 2\pi f B_w$, it is readily shown that a coupling coefficient for the ellipsoidal model, $C_{Ell\text{-}BT}$, is,

$$C_{Ell\text{-}BT} = 2\pi \left| \frac{a^2 u \mathbf{a}_v - b^2 v \mathbf{a}_u}{a^2 + b^2} \right|$$

expressed in units of V/m/Tesla-Hz

Thus, for a sinusoidal exposure

$$E_T = C_{Ell\text{-}BT} f B$$

Since a single value corresponds to each locus, percentiles are not applicable to the ellipsoidal model. Rather the loci at the periphery of each site were selected to represent maximal coupling.

The coupling coefficients for the ellipsoidal model, $C_{Ell\text{-}BT}$, and for the 99th percentile electric field in tissue, C_{BT99}, from anatomical modelling that were selected from the literature are shown in Table 1. Note that coupling coefficients for skin and fat are used as a surrogate for dose to peripheral nerve[8, 9], because the maximum dose to peripheral nerve is assumed to take place in a cutaneous receptor located near the interface between the skin and subcutaneous fat[10]. Dose to peripheral nerve has not been explicitly modelled as also noted by ICNIRP.

Electric fields

Homogeneous isotropic ellipsoids are not practical for estimating the distribution of tissue-specific electric fields from exposure to ambient electric fields. Electric field 99th percentile coupling coefficients based on grounded anatomical models in vertical electric fields are shown in Table 2, with most of the estimates based on a female anatomical model from Dimbylow[11]. Again, dose to peripheral nerve is based on an estimate of the maximum dose in the skin and fat within the modelled anatomy. The coupling listed for peripheral nerve is much larger than for the other sites because of the manner in which current from the field accumulates in the head-to-foot direction for a grounded individual, and concentrates in the lower extremities[12, 13]. For a person poorly grounded the coupling can be 40–50 % lower than that for a grounded person[14].

BASIC RESTRICTIONS

ICNIRP's BRs are specified for both 'Head' and 'Head & Body', while IEEE specifies BRs for four tissue sites: brain synapse (including the retina), CNS neuron (10-μm fibres), peripheral neuron (20-μm fibres) and heart. The tissue properties IEEE uses to establish BRs and ERLs for both the tiers are

Table 1. Magnetic field coupling coefficients, C_B, for sinusoidal magnetic field exposure (V/m/(Tesla-Hz)).

Site	C_{BT99} anatomical modelling	References	Comment	$C_{Ell\text{-}BT}$ IEEE, 2002	ICNIRP, 2010
Brain synapse (including retina)	0.322	Dimbylow[11]; Hirata *et al.*[7]	Caputa *et al.* [5] not used, low and inconsistent with others	0.326	0.660
Central neuron (10 μm)	0.571	Kavet *et al.*[31] Dimbylow[11]; Hirata *et al.*[7]; Caputa *et al.*[5]	Caputa *et al.* [5] result for arms in front not used, low and inconsistent with others	0.326	
Peripheral neuron (20 μm)	1.33	So *et al.*[9]; Caputa *et al.*[5]	Estimated with skin and/or fat dosimetry. Dimbylow[11] not used as only lateral orientation reported for skin and fat	1.03	1.20
Heart	0.668	Kavet *et al.*[31]; Dimbylow[11]; Hirata *et al.*[7]; Caputa *et al.*[5]	—	0.810	

Table 2. Electric field coupling coefficients, C_E, for sinusoidal magnetic field exposure (mV/(kV m^{-1}-Hz)).

Site	C_{ET99} anatomical modelling	Reference	Comment
Brain synapse (including retina)	0.011	Dimbylow[11]	—
Central neuron (10 μm)	0.046	Kavet *et al.*[31]; Dimbylow [11]	—
Peripheral neuron (20 μm)	0.58	Dimbylow[11]	Estimates based on skin and fat
Heart	0.080	Dimbylow[11]	Kavet *et al.*[31] less than half of Dimbylow[11]

reproduced from the IEEE Standard in Table 3 (along with the definitions for several relevant terms). In the central nervous system (CNS), the lowest recorded threshold for electrostimulation occurs at the synaptic level and manifests as conscious visual flashing or flickering sensations called phosphenes. This effect is transduced within retinal tissue[15] from coupling by an external electric or magnetic field (or by electrodes directly attached to the head)[16–18]. Although not in themselves considered adverse, the phosphenes signify a benchmark interaction of external fields with the CNS. Neural stimulation arises from well described interactions whereby electric fields induced along a neuron can trigger action potentials when a threshold is exceeded[19].

Figure 1 illustrates the comparison of ICNIRP and IEEE BRs for the lower and upper tiers. Although different in quantitative specifics, and with the exception of the 1–10 Hz frequency range, the two sets of BRs are qualitatively similar. First, with respect to phosphenes, ICNIRP's 'trough' from 10 to 25 Hz for both the tiers recognises that the phosphene response is reported as maximally sensitive to an exposure with a frequency at or ~20 Hz, an observation that goes back a century[16, 17, 20, 21]. ICNIRP estimates a peak phosphene threshold (i.e. rheobase) of 50–100 mV m^{-1} (35–71 mV m^{-1} rms)[22], and recommends an Upper Tier BR of 50 mV m^{-1} rms at 10–25 Hz, with a further reduction factor of 5 for the Lower Tier resulting in a BR of 10 mV m^{-1} rms. IEEE ties the magnetophosphene response to the 20 Hz, 8.14 mT rms threshold reported by Lovsund, with a threshold (rheobase) of 75 mV m^{-1} (53.0 mV m^{-1} rms) derived from the ellipsoidal dose model. Assuming this value is a population-median response, IEEE applies probability and safety factors to derive Lower and Upper Tier BRs at 20 Hz of 5.9 and 17.7 mV m^{-1}, respectively. The BRs rise proportionally with frequency above 20 Hz (e.g. they are 3-fold greater at 60 Hz than at 20 Hz), and remain at the 20 Hz values for frequencies <20 Hz.

For peripheral nerve stimulation (PNS), ICNIRP and IEEE rely on different sensory and aversive thresholds. ICNIRP cites a median sensory threshold (i.e. a rheobase) for PNS of 4 V m^{-1} for ELF (<3 kHz) stimulation based on dosimetry associated with human responses to magnetic resonance imaging pulse stimulation[9, 23]. Although ICNIRP refers to a threshold for 'intolerable stimulation' at 20 % above the population median threshold for perception (4 V m^{-1} peak), its BRs for Head & Body are based on the perception threshold. ICNIRP sets an Upper Tier BR of 0.8 V m^{-1} rms, which it states

Table 3. *Models for established thresholds of reaction: median *in situ* E-field thresholds[a,b].

Reaction	E_0 pk (V m^{-1})[c]	τ_e (ms)	f_e (Hz)
Synapse activity alteration, brain	0.075	25.0	20
10-μm nerve excitation, brain	12.3	0.149	3350
20-μm nerve excitation, body:			
IEEE (2002)	6.15	0.149	3350
Den Boer *et al.*[23] and So *et al.*[9]	3.8–5.8	0.36	1389
Cardiac excitation	12.0	3.00	167

[a]Interpretation of table as follows: $E_i = E_0$ for $t_p \geq \tau_e$; $E_i = E_0(\tau_e/t_p)$ for $t_p \leq \tau_e$.
Also, $E_i = E_0$ for $f \leq f_e$; $E_i = E_0\ (f/f_e)$ for $f \geq f_e$.
[b]Adapted from Reilly[10].
[c](V/m-pk) refers to the temporal peak of the electric field; terminology E_0 the minimum (rheobase) electric field strength in a strength–duration or strength–frequency relationship (V m^{-1}); E_i *in situ* electric field (V m^{-1}); f_e, upper transition frequency in a strength–frequency relation (Hz); τ_e transition duration in a strength–duration relationship, expressed in seconds (s); t_p phase duration (s); *Except for second row under '20-mm nerve excitation, body', reproduced from Table 6 of IEEE, 2002 (R2007); Definitions (quoted from IEEE, 2002 (R2007)); phase duration (t_p): The time between zero crossings of a waveform having zero mean. For a sinewave of frequency f, $t_p = 1/(2f)$. For an exponential waveform, t_p is interpreted as the duration measured from the waveform peak to a point at which it decays to 0.37 (e^{-1}) of its peak value; rheobase: The minimum threshold intensity in a strength–duration relationship (applicable to a stimulus duration that is long in comparison with the strength–duration time constant). Also applied to the minimum plateau in a strength–frequency relationship; strength–duration curve: The functional relationship between the threshold of excitation and the duration of an excitatory stimulus; strength–duration time constant (τ_e): The functional parameter in a strength–duration curve that describes the temporal inflection point between the rheobase and the rising threshold segment; strength–frequency curve: The functional relationship between the threshold of excitation and the frequency of an excitatory stimulus; upper transition frequency (f_e): In a strength–frequency curve, the frequency that corresponds to f_e is 1/2 τ_e.

as a 5-fold reduction factor from the perception threshold. (The reduction factor is actually 3.5 as it should be based on the rms perception threshold, which would be $4/\sqrt{2}$ V m^{-1}.) An additional 2-fold reduction results in a BR of 0.4 V m^{-1} rms for the Lower Tier. Above 3 kHz, the ICNIRP's Head & Body BR increases proportionally with frequency.

IEEE estimated a population median perception threshold (rheobase) for PNS of 6.15 V m^{-1} on the basis of a review of the literature. IEEE includes an 'adverse reaction factor' multiplier of 1.45 to the perception median to estimate the median pain threshold on the basis that perception itself is not an adverse effect. After factoring in a probability factor of 3 to the median to establish a lower population threshold for the Upper Tier—thus eliminating all but a statistically small fraction of the population from the probability of a painful response—IEEE factors in an additional factor of 3 for the Lower Tier. The resulting IEEE BRs for frequencies $\leq$3350 Hz are 2.10 V m^{-1} rms for the Upper Tier and 0.701 V m^{-1} rms for the Lower Tier, then increasing proportionally with frequency.

RESULTS

Magnetic fields

Magnetic field limits for both IEEE and ICNIRP are intended to protect against electrostimulation through direct coupling to excitable tissue, as there is no evidence to suggest that sensory perception of the field occurs[24]. IEEE's current magnetic field ERLs are derived from and keyed directly to the exposure values that induce the Lower and Upper Tier BRs within the ellipsoidal model at loci that correspond to the relevant tissues. For excitation of a brain (10 μm) neuron, peripheral neuron (20 μm) or cardiac tissue, the magnetic field corresponding to the rheobase was calculated. For CNS synaptic activation, the rheobase was derived from Lovsund's observation of 8.14 mT rms/20-Hz exposure as the most sensitive median threshold for inducing magnetophosphenes[17].

Figure 2 shows the plot of these magnetic fields for each tier across frequency for each tissue with the bottom trace, ERL, drawn along the minimum path (a whole-body uniform exposure is assumed). For both the tiers, the mechanism determining the ERL transitions from CNS synaptic activation below 751 Hz—as represented by the magnetophosphene response transduced in the retina—to PNS. (Note: The IEEE Standard indicates 759 Hz, with 751 Hz re-calculated for this paper.) In no case, do interactions in brain neurons or heart determine the minimum trace. As shown, the ERLs decline with frequency to 3350 Hz, the frequency that corresponds to the effective membrane time constant (τ_e) used by IEEE for 20-μm neurons (Table 3). For the Lower Tier, the ERL ramps down from 0.904 to

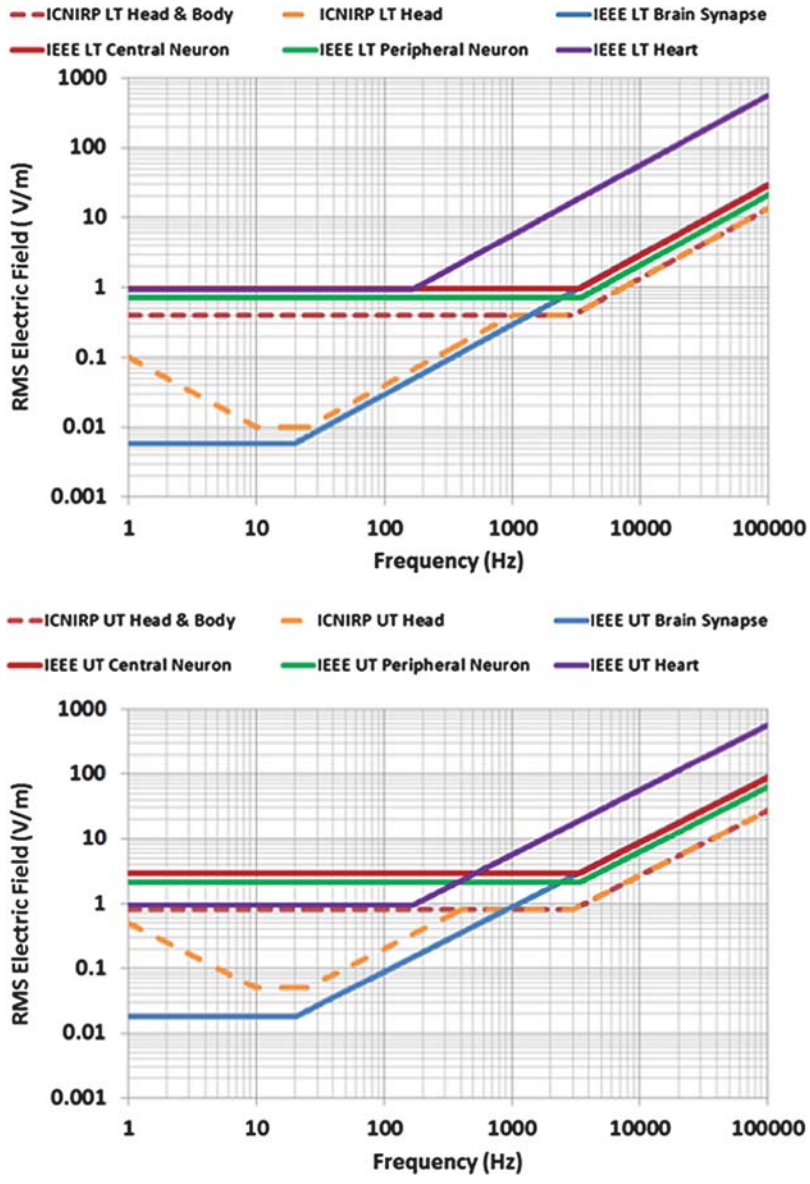

Figure 1. BRs for ICNIRP and IEEE: Lower Tier (top), Upper Tier (bottom).

0.203 mT at 3350 Hz and for the Upper Tier, from 2.71 to 0.608 mT. Using the 99th percentile coupling coefficients derived from the results of anatomical modelling (Table 1), while retaining the rheobase and time constants in the IEEE Standard (Table 3), the transition frequency shifts leftward to 582 Hz. This shift results in Lower Tier and Upper Tier values of 0.157 and 0.471 mT, respectively at frequencies $\geq$3350 Hz (Figure 3).

After the 2002 IEEE Standard was published, So *et al.*[9] and Den Boer *et al.*[23] reported peripheral nerve rheobase and chronaxie (the stimulus duration required to achieve the electrostimulation threshold at a stimulus strength of twice the rheobase) of 3.8 V m^{-1} and 0.36 ms, respectively. The level of change to the ERL curve that would result from adoption of the So *et al.* and Den Boer *et al.* (So/Den Boer) data as an alternative to the current IEEE Standard with respect to the limits based on painful stimulation of peripheral nerve was evaluated; the chronaxie value cited earlier serves as an estimate of the membrane time constant. Under such a presumption, the

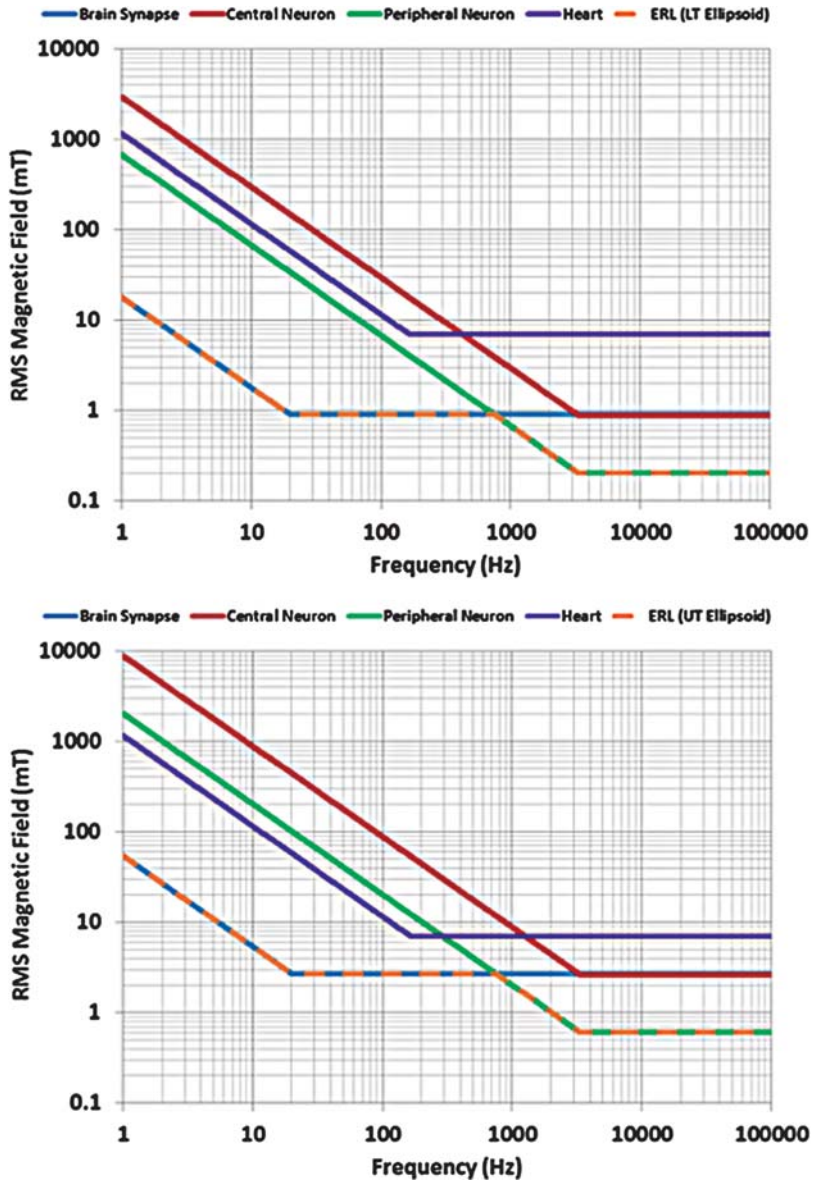

Figure 2. Magnetic field exposure levels that correspond to IEEE site-specific BRs. ERL shown as the minimum trace (dashed line): Lower Tier (top), Upper Tier (bottom).

ERLs would transition from a CNS synaptic activation basis to a PNS basis at 359 Hz, ramping down to 0.234 mT (Lower Tier) and 0.702 mT (Upper Tier) for frequencies $\geq$1389 Hz (Figure 3). Nonetheless, while recognising that experimental observations vary across laboratories, the rheobase and membrane time-constant values for peripheral nerve used in the IEEE, 2002 standard are well documented, with consistency across empirical and theoretical estimates[19].

For ICNIRP, the 99th percentile coupling coefficients from anatomic modelling results (Table 1) were used to derive the magnetic field exposure levels that correspond to the BRs for Head and for Head & Body with CNS synaptic activation and CNS neuron used for the Head calculations and peripheral nerve and heart used for 'Head & Body'. These results together with the ICNIRP ERLs for each tier appear in Figure 4. On the basis of the coupling coefficients used for the analyses in this

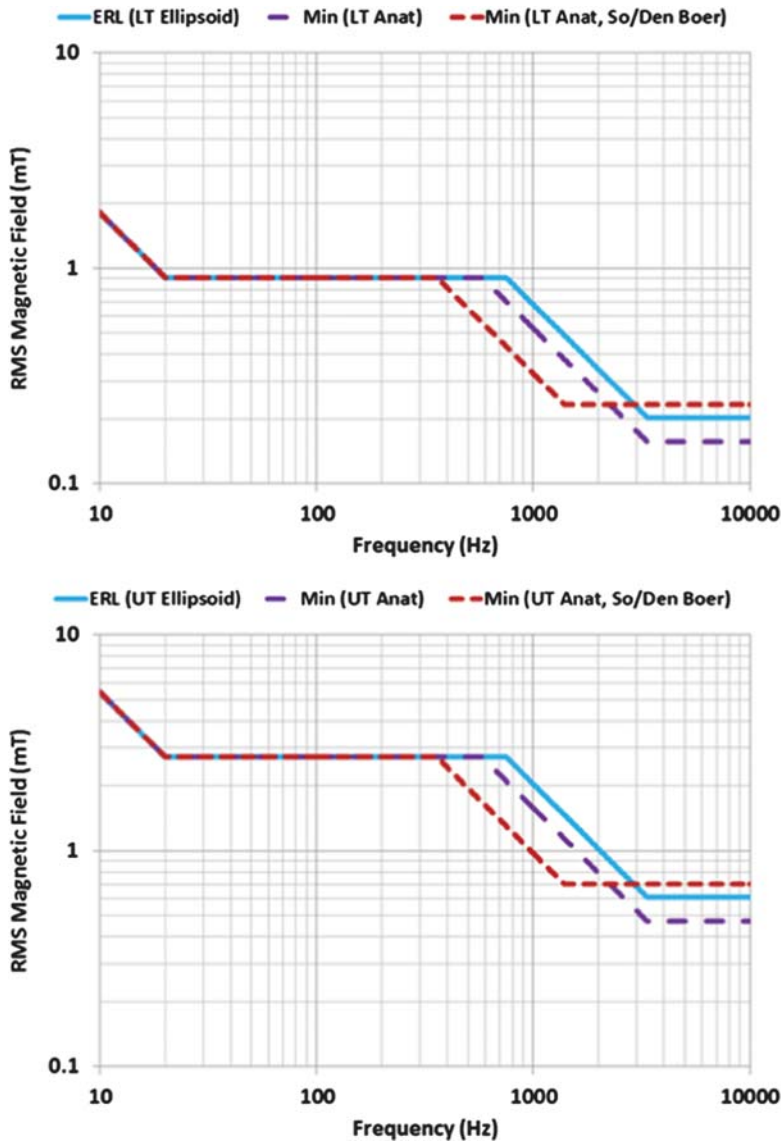

Figure 3. The minimum (Min) trace of the IEEE magnetic field ERL, using the ellipsoidal model in the current IEEE Standard (solid line); the minimum (Min) trace using coupling coefficients based on anatomic modelling and rheobase and membrane time constants for peripheral nerve in the current IEEE Standard (purple dashed line); and the minimum (Min) trace with the So/Den Boer values of rheobase and membrane time constant (red dashed line): Lower Tier (top), Upper Tier (bottom).

paper (Table 1, second column), Figure 5 shows the reduction factor from the minimum exposures (Min) at which the BR is coupled into Head and Head & Body to the ERL specified by ICNIRP for both the tiers. The ICNIRP Lower Tier ERL is a factor of at least 3.5 times lower than the 'Min' trace. The Upper Tier ERL is a factor of 3.5 lower than the 'Min' trace in the power frequency range and a factor of 2.0 lower above 300 Hz.

Electric fields

The 2002 IEEE Standard states:

> Exposure limits on environmental electric fields. . .are intended to avoid aversive or painful contact currents or spark discharges when an erect person touches a conductive path to ground. In this instance, the individual is the induction object if that person is insulated from

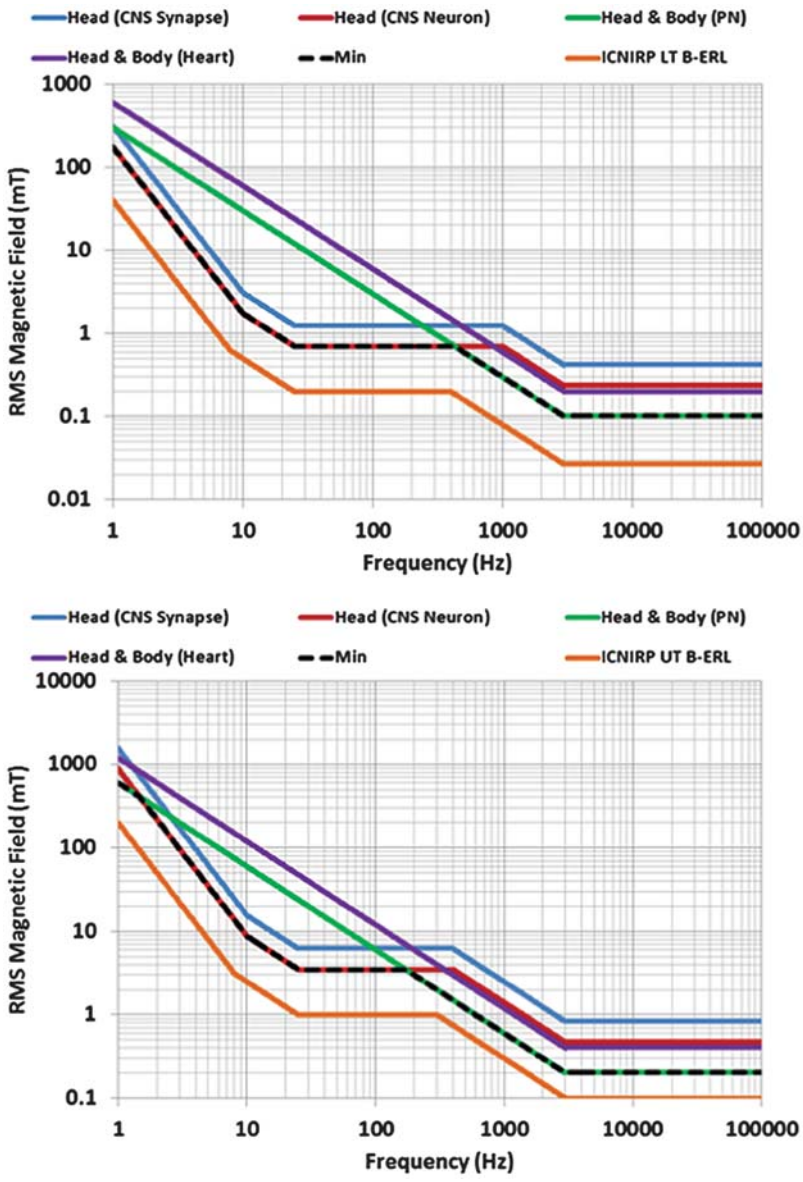

Figure 4. The ICNIRP ERLs are shown as the lowest curve (solid orange). Anatomically based coupling coefficients (Table 1) were applied to compute magnetic field exposure levels corresponding to ICNIRP's BRs with CNS synapse and brain neuron used for the Head and peripheral nerve and heart used for Head & Body. The curve describing the minimum (Min) computed fields are shown as dashed lines: Lower Tier (top), Upper Tier (bottom).

ground (rubber sole shoes, standing on an insulated surface, etc.).

Citing Reilly[10, 25], the 2010 ICNIRP Guideline states:

> . . .Exposure to low-frequency electric fields causes well-defined biological responses, ranging from perception to annoyance, through surface electric-charge effects.

The electric field ERLs for ICNIRP and IEEE are shown in Figure 6. For IEEE (Figure 6, top) the left segment of the standard is specified to protect against potentially aversive effects of spark

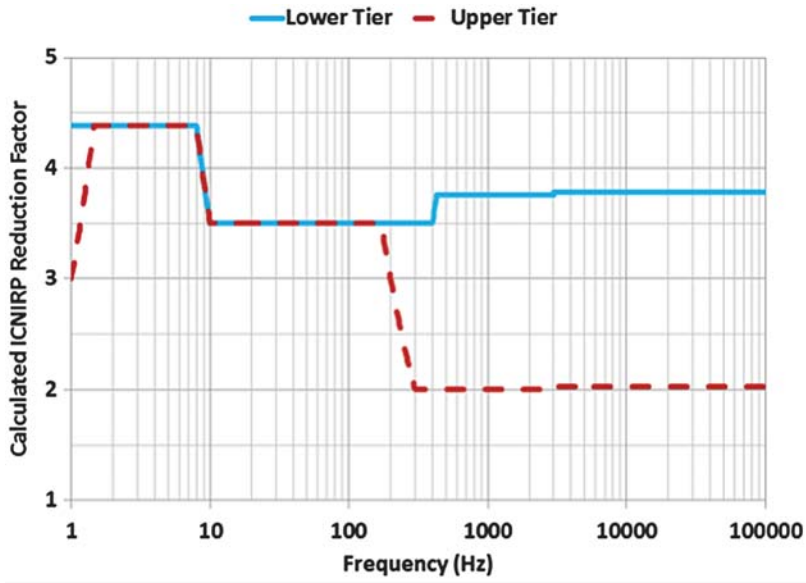

Figure 5. The ratio of the magnetic field exposure level that couples to tissue with the 99th percentile *in situ* electric field at the BR to the ICNIRP ERL as a function of frequency.

discharge, while the down-sloping segment on the right of the chart is specified to protect against potentially aversive effects of contact current. For an erect person situated in a vertical electric field, short-circuit current for contact of an ungrounded person with a grounded object is estimated as the current through the feet of a free-standing well-grounded person[26, 27].

The 'break' frequency—363 Hz for the Lower Tier and 272 Hz for the Upper Tier—marks the junction of the flat and sloping segments for the IEEE Standard. (Note: The IEEE Standard indicates 368 Hz for the Lower Tier, with 363 Hz re-calculated for this paper.) For ICNIRP (Figure 6, bottom):

> . . .the electric field reference level for occupational exposure up to 25 Hz includes a sufficient margin to prevent stimulation effects from contact currents under most practical conditions. Between 25 Hz and 10 MHz the reference levels are based on the basic restriction on induced electric fields only and might thus not provide a sufficient margin to prevent stimulation effects from contact currents under all possible conditions in that frequency band.
>
> The electric field reference levels for general public exposure up to 10 MHz prevent adverse indirect effects (shocks and burns) for more than 90 % of exposed individuals. In addition, the electric field reference levels for general public exposure up to 50 Hz include a sufficient margin to prevent surface electric-charge effects such as perception in most people.

The aforementioned exercise for magnetic fields was conducted to assess whether coupling of exposures below current ERLs produced *in situ* electric fields at or above BRs when dosimetry was based on anatomical modelling (rather than the ellipsoidal model). Similarly, we assessed whether electric field exposure levels lower than the ERLs induce electric fields in tissue equal to or greater than the BR. In other words, could the basis of the electric field exposure limit shift from one based on aversive indirect effects to one based on direct coupling? The scenario used by both IEEE and ICNIRP is that of a free-standing well-grounded adult in a vertical electric field. The magnitude of the electric field is set to the level present with the person absent (uniform, vertical field). The results are presented first for the peripheral nerve rheobase and membrane time constant used in the IEEE Standard, and then for the So/Den Boer values of these parameters. Again, the 99th percentile electric field coupled into tissue is the dose criterion.

The results (Figure 7) show the IEEE ERL layered upon the curves of exposure levels corresponding to the BR for the four tissue sites with the trace labelled, 'Min', denoting the lowest field value for any site across frequency. For reference, the ICNIRP ERL is also shown. For the Lower Tier, the exposure curve for peripheral nerve crosses the

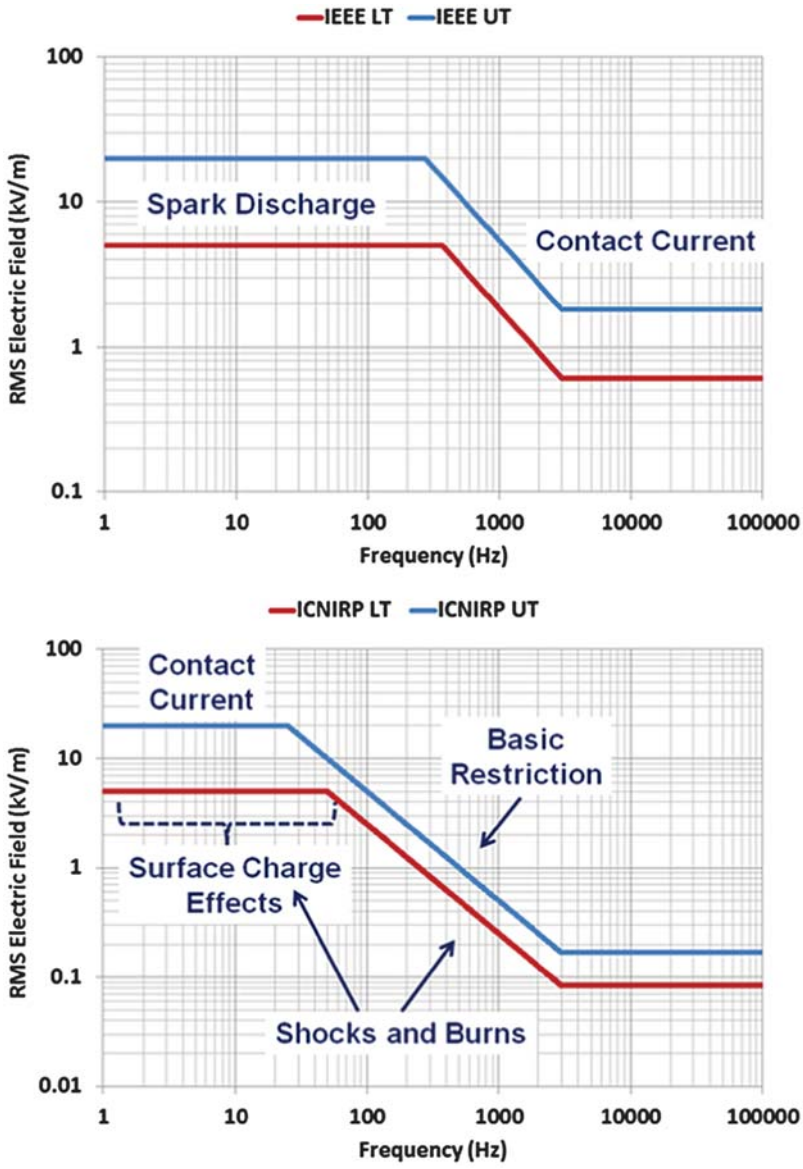

Figure 6. Electric field ERLs: IEEE (top), ICNIRP (bottom). LT, Lower Tier, UT, Upper Tier.

ERL at 240 Hz, dropping to 66.2 % of the ERL at 363 Hz until 3 kHz, at which point it transitions to 58.5 % of the ERL at frequencies $\geq$3350 Hz. For the Upper Tier, the exposure curve for peripheral nerve crosses the ERL at 180 Hz, dropping to 66.2 % of the ERL at 272 Hz until 3 kHz, at which point it transitions to 59.3 % of the ERL at frequencies $\geq$3350 Hz.

If peripheral nerve is characterised by the So/Den Boer values of the rheobase and membrane time constant (3.8 V m^{-1} and 0.36 ms, respectively)—as done earlier for magnetic fields—for the Lower Tier, the ERL crossing frequency for peripheral nerve is 149 Hz, dropping to 40.9 % of the ERL at 363 Hz until 3 kHz, at which point it transitions to 87.2 % of the ERL at frequencies $\geq$3350 Hz (Figure 8, top). For the Upper Tier, the exposure curve for peripheral nerve crosses the ERL at 111 Hz, dropping to 40.9 % of the ERL at 272 Hz until 3 kHz, at which point it transitions to 88.5 % of the ERL at frequencies

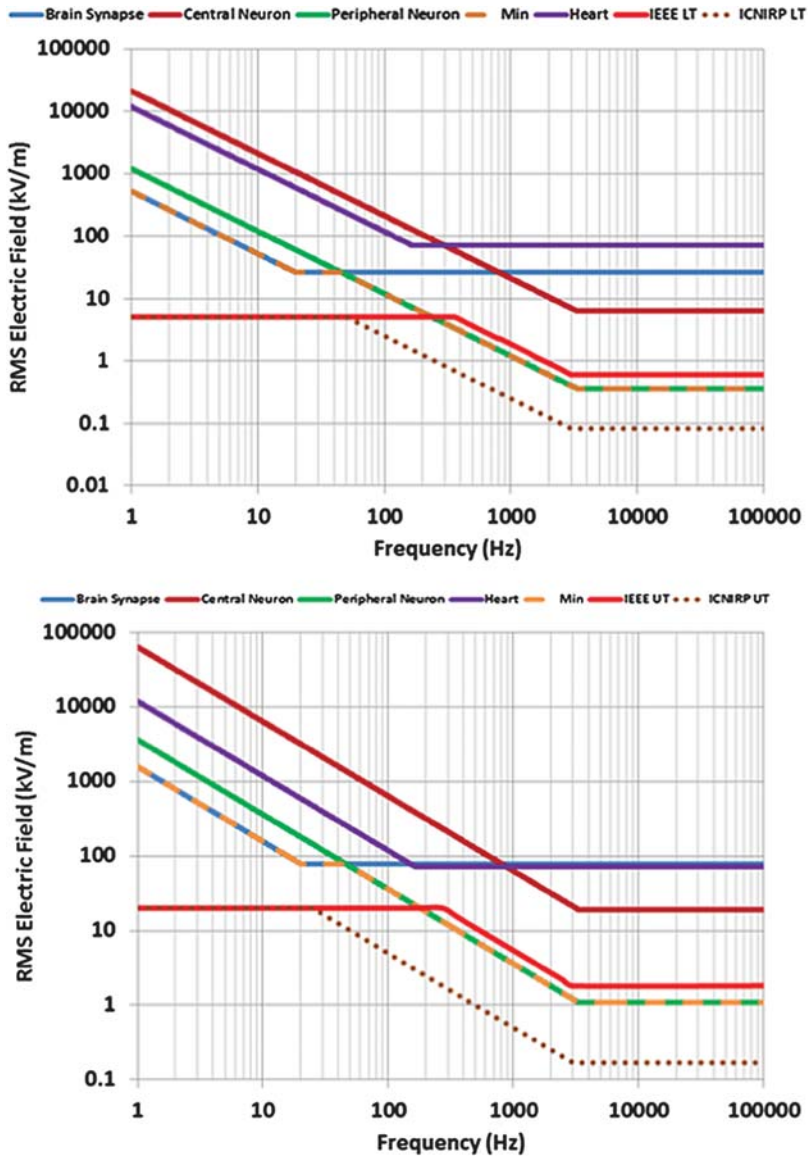

Figure 7. Electric field exposure levels that correspond to IEEE site-specific BRs, using the coupling coefficients in Table 2. Dashed trace labelled 'Min' is the minimum value for any site. ERLs shown for IEEE (light red) and ICNIRP (brown dotted line): Lower Tier (top), Upper Tier (bottom).

≥3350 Hz (Figure 8, bottom). The 'Min' traces alone for both the peripheral nerve models are layered on the IEEE and ICNIRP ERLs in Figure 8. Although the exposure levels tied to the BRs fell below IEEE ERLs, in no case did they fall below ICNIRP's ERLs for either Tier. Thus, for both the sets of parameters for peripheral nerve, the BR is exceeded for exposures lower than the IEEE's ERLs beyond frequencies roughly ranging from 100 to 250 Hz.

For ICNIRP, the ERLs for both the tiers remained below the electric field exposure values that would couple to BR levels in tissue (Figure 9). For the Lower Tier, the closest approach of the BR-based electric field curves was 75 % greater than that of the ERL between 25 and 50 Hz, based on brain dosimetry (CNS neuron). For the Upper Tier, the closest approach was at 25 Hz, 220 % of the ERL and again based on brain dosimetry.

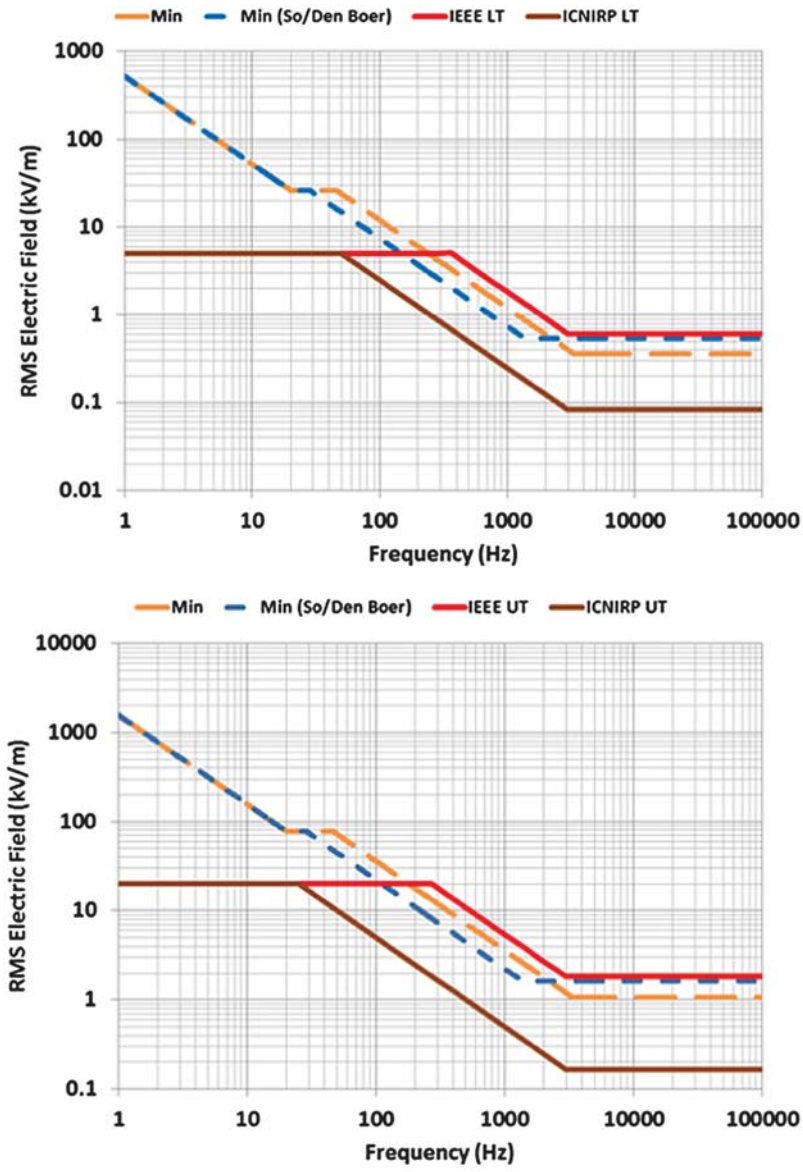

Figure 8. The Min trace of the IEEE electric field ERL, using the coupling coefficients based on anatomical modelling and rheobase and membrane time constants for peripheral nerve in the current IEEE Standard (orange dashed line) and using the So/Den Boer values of rheobase and membrane time constant (blue dashed line). The ICNIRP electric field ERL (brown line) shown for reference: Lower Tier (top), Upper Tier (bottom).

DISCUSSION

This paper illustrates that anatomically based dosimetric computations of electric fields induced in tissue from external electric and magnetic fields can be used to assess the extent to which electric and magnetic field exposure limits in the ICNIRP Guideline and IEEE Standard provide assurances that the BRs will not be exceeded. The coupling coefficients and electrical properties of tissue used here may not have been those that others would choose, but served the purpose of showing how these factors may affect the relationship of ERLs to BRs. Coupling coefficients were especially found to be useful in comparing models and thresholds

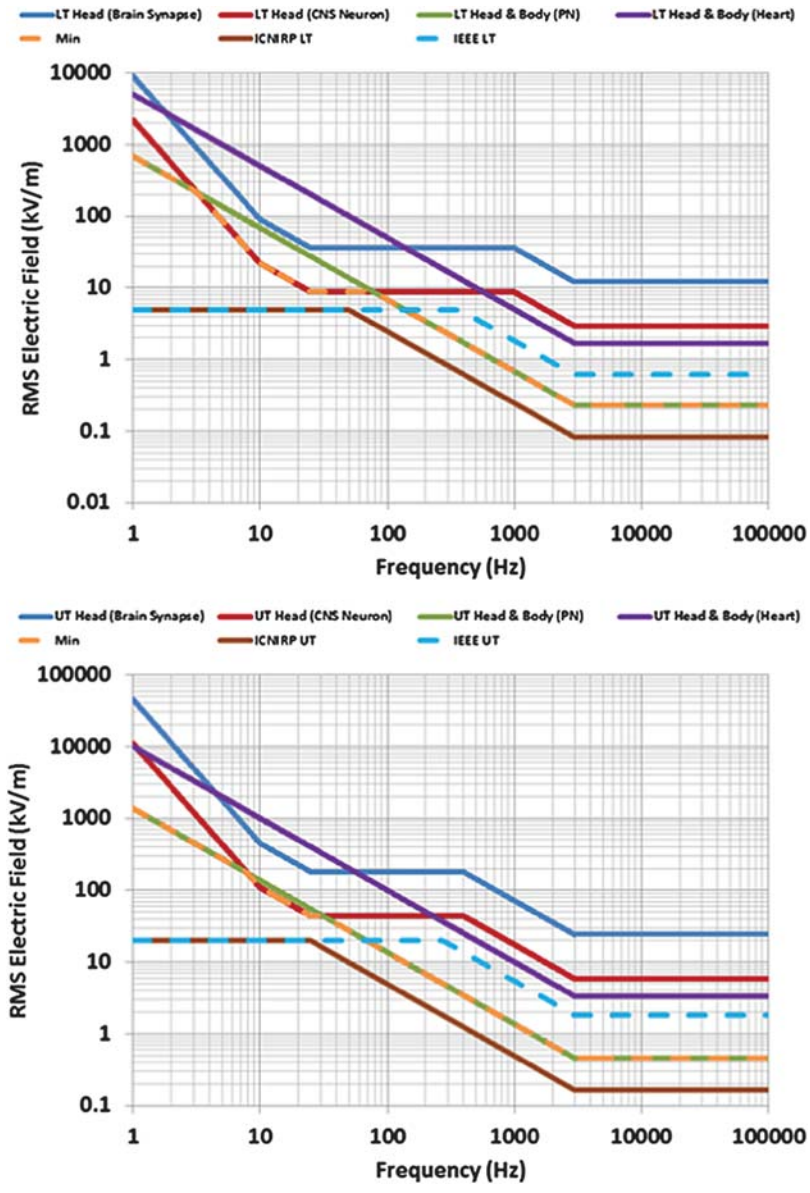

Figure 9. Electric field exposure levels that correspond to ICNIRP Head and Head & Body BRs, using the coupling coefficients in Table 2. Dashed trace labelled 'Min' is the minimum value for any site. ERLs shown for ICNIRP (brown line) and IEEE (blue dashed line): Lower Tier (top), Upper Tier (bottom).

for different anatomic sites, an approach that may prove useful for future evaluations. The analyses, while suggesting a framework for incorporating anatomically correct dosimetry with tissue properties into exposure limit formulation, were not intended to provide recommendations for revisions to the standing exposure limits of either of the two organisations.

The analyses in this paper dealt with adult rather than child models (the highest exposures are usually in occupational settings). For electric fields, induced short-circuit current (I_{sc}) scales as the square of height at a given field strength and frequency[26, 27]. Thus, as a first-order approximation, for a 1.1-m tall child, I_{sc} would be about 40 % of I_{sc} in a 1.75-m tall adult. However, the smaller cross-sectional areas of

a child's anatomy scale doses upward. For an adult–child comparison, the example of an ungrounded individual located in a vertical electric field contacting a grounded object can be used. Using the adult and child model data for contact current dose to bone marrow from Dawson *et al.*[28] the combined effect of height and cross section would result in 20–30 % greater electric field in the lower arm of the child, compared with the adult for the same electric field. Thus, in this case, the effect of cross-sectional area more than offset the effect of height with respect to dose to tissue. For magnetic fields, dose to tissue scales in concert with the linear dimensions of the exposed individual. Using the same adult and child models referenced earlier, in which the child's height was 62 % of the adult height, Dawson *et al.* reported that the child's average and 99th percentile doses are close to 60 % of the adult values for all tissue sites except brain, which has relatively larger dimensions for the child (~86 % of adult)[29].

Magnetic fields

The given population median magnetophosphene threshold of 8.14 mT determined IEEE's Upper and Lower Tier ERLs at the lower end of the frequency range. Nonetheless, recent anatomical dosimetry (Table 1) enabled an estimate of a coupling coefficient for adult retina of 0.322 V/m/(Tesla-Hz) for the 99th percentile, compared with 0.326 V/m/(Tesla-Hz) for the ellipsoidal model (an estimate of the tissue maximum), a very close correspondence. The anatomically based value leads to a rheobase estimate for the magnetophosphene response in retina of 0.074 V m^{-1} (compared with 0.075 V m^{-1} for the ellipsoidal model), consistent with ICNIRP's range of values.

More significantly, with the skin and fat serving as a surrogate for peripheral nerve, the 99th percentile coupling of magnetic fields to those sites was 29 % greater than coupling in the ellipsoidal model for the locus selected to represent peripheral nerve. With stronger coupling, the BR for peripheral nerve would be coupled in the anatomical model with lower fields at each frequency compared with the ellipsoidal model in direct proportion to the ratio of the coupling coefficients. The effect is that the peripheral nerve exposure curve (the exposures as a function of frequency that produce the 99th percentile dose in peripheral nerve equal to the BR) for both the tiers is shifted downward by 23 % relative to the curve in the ellipsoidal model in accordance with that ratio. This resulted in an intersection of the peripheral nerve exposure curve with the magnetophosphene curve at 582 Hz compared with 751 Hz for the ellipsoidal model (Figure 3). The basis for this shift likely concerns the greater complexity of a human anatomical model and the greater probability of the induced electric field encountering sites where axons bend or terminate, which are more sensitive to stimulation than straight axon segments[19, 30]. Further, if based on recent studies[9, 23], the peripheral nerve membrane was characterised with a 3.8 V m^{-1} rheobase (instead of 6.15 V m^{-1} as in the IEEE Standard) and a membrane time constant (actually estimated from the reported chronaxie) of 0.36 ms (instead of 0.149 ms as in the IEEE Standard), the curve is shifted downward by an additional 38 %. It crosses the phosphene threshold at 359 Hz, amounting to a net decrease of 48 % from the peripheral nerve values in the ellipsoidal model, based on the multiple of the respective ratios of both the coupling coefficients (1.03/1.33) and rheobases (3.8/6.15). With the So/Den Boer rheobase and the membrane time constant used for peripheral nerve, the transition to a horizontal trace occurs at 1389 Hz, corresponding to the revised time constant and the limiting exposure marginally exceeds that of the ellipsoidal model for frequencies >2906 Hz. Despite the downward shifts of the peripheral nerve exposure curves due to coupling and alternative rheobase assumptions, the peripheral nerve values at power frequencies are well above the exposure limits driven at those frequencies by the BR for synaptic activation. At 60 Hz (50 Hz), and for both Tiers, the values of the peripheral nerve exposure curves are 12.7 (15.0)-, 9.7 (11.6)-, and 6.0 (7.2)-fold greater than the ERL values for the ellipsoidal model, the anatomical model with rheobase and time constant values used in the IEEE Standard, and the anatomical model with So/Den Boer rheobase/time constant values, respectively.

Unlike the approach taken by IEEE, ICNIRP's ERLs do not appear to be linked directly to its BRs. Using CNS synapse and CNS neuron to represent the Head, and peripheral nerve and heart to represent Head & Body, the anatomical coupling coefficients shown in Table 1 indicate that, at lower frequencies, CNS neuron would determine the minimum trace of the exposures corresponding to the BRs, with PNS intersecting the central neuron trace at 428 Hz for the Lower Tier and at 171 Hz for the Upper Tier. The intersection with the synaptic activation curve (representing the retinal locus) would be at 241 and 97 Hz, respectively. In either case, through the lower range of frequencies at which power systems operate, and presumably most exposure occurs, ICNIRP has more stringent magnetic field ERLs despite less stringent BRs compared with IEEE. This is at least partially attributable to an additional reduction factor of nominally 3 by ICNIRP to account for dosimetric uncertainty. However, ICNIRP also uses a coupling coefficient corresponding to brain [upper estimate of 0.66 V/m/(Tesla-Hz)], which is more than double the coefficient that was assigned to the retina [0.322 V/m/

(Tesla-Hz)] on the basis of magnetophosphenes, which is the response that defines the limits for the lower end of the frequency range.

Electric fields

Using skin and fat as a surrogate for peripheral nerve, the analyses carried out in this study indicate that electric field exposures that correspond to the BR for peripheral nerve—as represented by the 99th percentile *in situ* field—cross the IEEE electric field ERLs, an observation that might not have been apparent without anatomical dosimetry. For the Lower Tier and the Upper Tier, when the rheobase and membrane time constants in the IEEE Standard are used, the peripheral nerve trace crosses at 240 and 180 Hz, respectively. With the So/Den Boer values of rheobase and membrane time constant specified earlier, these frequencies fall to 149 and 111 Hz, respectively. However, in our estimation, the preponderance of electric field exposures occurs at the power frequencies from overhead power lines or buswork in electric utility facilities. At 60 Hz (50 Hz), the peripheral nerve electric field exposure corresponding to the BR exceeds the ERL by a factor of 4.0 (4.8) for the Lower Tier and by 3.0 (3.6) for the Upper Tier. For the So/Den Boer values of rheobase and membrane time constant these values are, respectively, 2.5 (3.0) and 1.9 (2.2). The ERLs for ICNIRP are flat up to 25 and 50 Hz for the Lower and the Upper Tiers, respectively, and as they ramp down at those frequencies, the Head and Head & Body exposure curves that correspond to ICNIRP's BRs do not cross the ICNIRP ERL for either Tier. In comparison the IEEE's ERLs are flat to 363 and 272 Hz, for the Lower and the Upper Tiers, respectively, which as described earlier intersects the curves that reflect exposure corresponding to IEEE's BRs for peripheral nerve.

General comments

The use of skin and fat as surrogates for peripheral nerve, although used in previous publications[8, 9], and relied on by ICNIRP for the 2010 Guidelines has not to the authors' knowledge, been validated rigorously. Since magnetic field induction is maximal towards the periphery of anatomical structures increasing with cross-sectional area, and the cross-sections of the limbs are small compared with those of the torsos, the 99th percentile induced electric fields associated with fat and skin was expectedly associated with the torso periphery[9].

For electric field exposures, induced currents concentrate in the lower extremities for a well-grounded person, and the 99th percentile coupling coefficients for skin and fat may conceivably be associated with the ankles and feet. The scenario of an ungrounded individual, e.g. a person wearing insulative footwear, would likely be more common than the worst-case grounded scenario. In that case, electric field coupling to the body may decrease by roughly 40–50 % (except for possibly the neck) depending on anatomical site[14], and the site of maximal coupling to peripheral nerve would likely be along the lower limb, rather than at its extremity (ankle or foot). Therefore, if the coupling coefficient for peripheral nerve was over-estimated for this analysis and/or a person is not fully grounded, the exposure levels corresponding to the BRs for peripheral nerve would be close to or even possibly above the ERLs. To reiterate, at the power frequencies (50–60 Hz), the BRs for both ICNIRP and IEEE would not be expected to be exceeded at exposure levels of 5 kV m^{-1} (IEEE Lower Tier) or 20 kV m^{-1} (IEEE Upper Tier).

The IEEE Standard considers synaptic activation, although manifested as a visible phosphene, to also have possible transduction sites in the brain. The Standard states: 'Clearly adverse reactions that may be attributable to CNS reactions (tiredness, headaches, muscle spasms, persistent afterimages) are reported in connection with phosphene threshold experiments. It is unlikely that the phosphenes themselves were causing the reported adverse reactions. A plausible explanation is that the adverse effects were due to electrostimulation of brain neurons in accord with the synapse mechanism...' The data in Table 1 indicate that based on anatomically correct dosimetry, coupling of external magnetic fields to brain is ~70–80 % greater than that to the retina. In the ellipsoidal model, the coupling coefficients for the loci corresponding to these two sites were identical. The authors are not aware of studies in which adverse reactions (such as those described earlier) occurred at exposure thresholds lower than those that produced phosphenes, as would be the case if brain and retina had equal sensitivities to induced fields. Either synaptic activation in the brain with the effects stated occurs with higher *in situ* thresholds compared with retina, or the other adverse reactions described may be conceivably linked to the magnetophosphene. At present, the answer to this question is not apparent.

In conclusion, improved refinements in anatomical modelling can assist in the formulation of exposure limits for electric and magnetic field based on established, yet still evolving, knowledge of biophysical mechanisms that can initiate biological effects. Further investigations into parameters that characterise peripheral nerve thresholds together with improved estimates of dose to peripheral nerve would be valuable contributions, as would be a fuller elaboration of the mechanisms responsible for synaptic activation by local electric fields in the CNS.

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