AN ANALYSIS OF DIFFERENCES IN THE LOW-FREQUENCY ELECTRIC AND MAGNETIC FIELD EXPOSURE STANDARDS OF ICES AND ICNIRP

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Abstract—**Technical factors accounting for differences in low-frequency (0–3 kHz) standards of IEEE C95.6 and ICNIRP are identified. These factors are related to thresholds of adverse reactions, safety factors, probability factors, thresholds for different tissue types, magnetic induction models, and induced current and spark discharges with E-field exposure. This paper summarizes technical factors accounting for differences between the two standards and recommends resolution of those factors.**
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INTRODUCTION

THE INTERNATIONAL Committee on Electromagnetic Safety (ICES)—an international group under the auspices of The Institute of Electrical and Electronic Engineers (IEEE)—recently developed Standard C95.6 for human exposure to electric and magnetic fields in the frequency range 0–3 kHz (ICES 2002). Another international standard that included the same frequency range was published by The International Commission on Nonionizing Radiation Protection (ICNIRP 1998a and b). Despite the fact that the ICES and ICNIRP standards are based on similar objectives and published data, their exposure limits differ substantially in parts of the frequency spectrum.

The standards of ICES and ICNIRP are advisory and carry neither a mandate for compliance nor a mechanism for enforcement. Nevertheless, these standards have been consulted by standard-setting agencies in diverse countries that have issued their own standards, which, in some cases, may differ substantially from those of ICES and ICNIRP. Because of the international advisory status and recognized expertise of ICES and ICNIRP, it is valuable to focus attention on their standards.

The purpose of this paper is to make explicit the underlying technical differences between the two standards and to identify areas needing clarification or further research. The goal is to further the process of harmonization between the two standards so that eventually a single international advisory consensus might emerge for consideration by countries or agencies that are developing their own standards.

Because of my role as the Working Group leader responsible for the ICES standard, I cannot avoid a preference for the rationale and conclusions of the ICES standard. Nevertheless, I have attempted to identify without bias the technical factors that account for the differences in the two standards. By identifying these factors, I hope to facilitate a dialog between ICES and ICNIRP.

GENERAL OBJECTIVES OF THE STANDARDS

Both standards provide two tiers of protection. For ICES they are the general public and individuals in a "controlled environment."† For ICNIRP they are (a) the general public; (b) occupationally exposed individuals. Populations of the ICES and ICNIRP tiers are not necessarily coincident, although they are quite similar. Both standards define restrictions on the electrical forces induced within the tissue (*Basic Restrictions* = BRs), and also on the environmental fields (*Maximum Permissible Exposure Levels* = MPE levels in ICES; *Reference*

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† The controlled environment is defined by ICES as: an area accessible to those who are aware of the potential for exposure as a concomitant of employment, to individuals cognizant of exposure and potential adverse effects, or where the exposure is the incidental result of passage through areas posted with warnings, or where the environment is not accessible to the general public and those individuals having access are aware of the potential for adverse effects. The occupationally exposed population of ICNIRP is defined as: adults who are generally exposed under known conditions and are trained to be aware of potential risk and to take appropriate precautions.

Levels = RLs in ICNIRP). ICES defines BRs as the in situ electric field; ICNIRP defines BRs as in situ current density. E-field and current density can be related if tissue conductivity, σ, is known.

For both standards, the BRs are the fundamental restrictions. The MPEs or RLs, which are derived from the BRs under conservative assumptions, are provided as an aid to determining if the BRs are met. MPE and RLs are defined in both standards as the environmental electric and magnetic field in the case of field exposure, and as conducted current in the case of contact with grounded conductors. Both standards protect against short-term reactions to electrostimulation of nerve and muscle; evidence for effects from long term exposure at levels below those producing immediately observable adverse reactions were judged by both to be insufficient for setting exposure standards.

Although ICES had access to additional data due to its later publication date, this access does not account for differences between the two standards. Considering that the two groups had nearly identical objectives, that the publications available to them were essentially the same, and that they claim to have based their standards on science rather than other considerations, their standards should not differ substantially. This is not the case. The purpose of this paper is to make clear the technical reasons for their differences in the frequency regime in which they overlap (i.e., 0–3 kHz).

BASIC RESTRICTIONS

Strength-duration and strength-frequency laws

Tables 1 and 2 list the BRs of ICES and ICNIRP. ICES differentiates BRs by tissue type, while ICNIRP does not. Other differences include their metrics and frequency dependencies, as well as the numerical limits.

Table 1. Basic restrictions of ICES.[a,b,c]

		General public	Controlled environment
Exposed tissue	f_e (Hz)	E_o − rms (V/m)	E_o − rms (V/m)
Brain	20	5.89×10^{-3}	1.77×10^{-2}
Heart	167	0.943	0.943
Hands, wrists, feet and ankles	3,350	2.10	2.10
Other tissue	3,350	0.701	2.10

[a] Interpretation of Table is as follows: $E_i = E_o$ for $f \le f_e$; $E_i = E_o\ (f/f_e)$ for $f \ge f_e$.
[b] In addition to the listed restrictions, exposure of the head and torso to magnetic fields below 10 Hz shall be restricted to a peak value of 167 mT for the general public, and 500 mT in the controlled environment.
[c] The parameter E_i is the in situ E-field; E_o is the minimum (rheobase) field at frequencies below f_e; f_e is a frequency parameter differentiating the point on the strength-frequency curve above which thresholds converge to a line proportional to frequency, f.

Table 2. Basic restrictions of ICNIRP.[a]

		General public	Occupational
Exposed tissue	freq. range (Hz)	J − rms (mA/m^2)	J − rms (mA/m^2)
Non specific	0–1	8	40
	1–4	8/f	40/f
	4–1,000	2	10
	10^3–10^5	f/500	f/100

[a] Notes: (a) f = frequency in Hz; (b) J = in situ current density.

These differences are reviewed below with reference to Tables 3 and 4, which summarize the various factors.

ICES derived BRs as follows: (a) identify population median thresholds of minimum reaction in different tissue types, (b) convert these to adverse reaction levels with an adverse reaction multiplier,[‡] (c) define a low probability (at most 1%) adverse reaction level, (d) apply a safety factor to allow for exceptionally sensitive individuals and various uncertainties. ICES defined BRs (Table 1) through either a strength-duration (S-D) function that applies to pulsed fields, or a strength-frequency (S-F) function for sinusoidal fields. Two parameters are required in this formulation: (1) *rheobase* (minimum plateau); (2) S-D time constant, τ_e, or S-F frequency constant, f_e as indicated below:

$$E_i = E_o \text{ for } t_p \ge \tau_e \quad (1a)$$

$$E_i = E_o(\tau_e/t_p) \text{ for } t_p \le \tau_e \quad (1b)$$

in the case of S-D functions, and:

$$E_i = E_o \text{ for } f \le f_e \quad (2a)$$

$$E_i = E_o(f/f_e) \text{ for } f \ge f_e \quad (2b)$$

$$f_e = 1/(2\tau_e) \quad (2c)$$

for S-F functions, where E_o is the rheobase E-field, E_i is the allowable in situ E-field, t_p is the phase duration of a pulsed waveform, f is the frequency of a sinusoidal waveform, τ_e is the time constant that separates the minimum plateau from the rising portion of an S-D curve, and f_e is the frequency constant that separates the minimum plateau from the rising portion of an S-F curve. The parameters in Table 1, which are based on experimental data and theoretical models, are differentiated by tissue type. In Table 3, the ICES data have been compiled

[‡] A multiplier that converts an exposure level causing a threshold reaction to one causing an adverse reaction.

Table 3. Identifiable basis for differences in basic restrictions between ICES and ICNIRP standards.[a]

Item (basic restrictions)	ICES	ICNIRP
1) Basic Restriction in situ metric	E-field	Current density
2) Median rheobase adverse threshold	E_i = 53 mV/m (rms)	NS
3) In situ rheobase threshold to which safety factor is applied	E_i = 17.7 mV/m	J = 100 mA/m^2 (E_i = 500 mV/m)
4) Probability level in (item 3)	$P < 1\%$	NS
5) Safety factor, F_s:		
general public	1/3	1/50
contr. env./occup.	1	1/10
6) Min. BR after application of F_S		
general public	E = 5.9 mV/m	J = 2 mA/m^2 (E = 10 mV/m)
contr. env./occupational	E = 17.7 mV/m	J = 10 mA/m^2 (E = 50 mV/m)
7) Upper transition frequency in S-F curve for CNS effects	20 Hz	1,000 Hz
8) Lower transition frequency in S-F curve for CNS effects	None	4 Hz
9) Mechanism for min. CNS effect	Synapse potential alteration	NS
10) Distinct BRs for different tissue type	Yes	No
11) Applicable area of min. BR in CNS	Brain	Head & torso
12) Reduction below adverse MHD effects		
general public	1/9	1/50
contr. env./occupational	1/3	1/10

[a] Notes: σ = 0.2 S/m in $E = J/\sigma$; NS = not stated; Listed BRs are rheobase values (minimum thresholds in a S-F function) for the most sensitive organ (the brain or CNS); BRs of ICES apply to synapse interactions in the brain; E_i for ICNIRP calculated from J using σ = 0.2 S/m; CNS = central nervous system; MHD = magnetohydrodynamic.

Table 4. Identifiable basis for differences in MPEs/RLs between ICES and ICNIRP (whole body exposure).

Item (MPEs or RLs)	ICES[a]	ICNIRP
1) Magnetic field induction model	Ellipsoid (body, torso, brain, limb)	Circular loop (r = 64 cm)
2) E-field induced current (1.8 m tall person, insulated, touch ground, vertical field)	*I(touch)* 0.5 mA, public 1.5 mA, contr. env.	*J(neck)* 2 mA/m^2, public 10 mA/m^2, workers
3) E-field transition frequency	3,000 Hz	3,000 Hz public 820 Hz, workers
4) Capped E-field	5 kV/m, public[b] 20 kV/m contr. env.	10 kV/m, public 20 kV/m, workers
5) Joint BR and MPE for E-field exposure	BR *AND* MPE	BR *OR* MPE (?)

[a] ICES MPEs are for whole body exposure.
[b] For general public, ICES E-field MPE = 10 kV/m in transmission line ROW.

only with respect to synaptic effects in the brain, which have the lowest rheobase BRs.

Basic restriction metric (Table 3, item 1)

ICES defines BRs as the induced (in situ) E-field, rather than current density, J, as in ICNIRP and most other previous standards. The E-field relates in situ electrical forces to cellular polarization—the fundamental mechanism of electrostimulation (Reilly 1998, 2002, 2003).

Although one can relate these two parameters by $J = E\sigma$, where σ is the conductivity of the medium surrounding the neuron, the conversion introduces an additional parameter (σ) about which there may be additional uncertainty in an applied situation. With the uniform-conductivity magnetic induction models used by ICES and ICNIRP, the induced E-field metric does not depend on σ.

Despite differences in the BR metric chosen by ICES and ICNIRP, this is not the greatest factor in the BR differences between the two standards. Other factors, as noted below, are most likely of greater relevance. However, the choice of E vs. J is more significant if one derives BRs or determines compliance using a detailed anatomical induction model, for which the calculated spatial peak of E and J do not necessarily occur at the same location within the subject (Dawson et al. 1999).

Fig. 1 illustrates BRs vs. frequency for both standards. To plot them on a single graph, we equate E and J as used in the two standards using σ = 0.2 S m^{-1}, which is the value cited by ICNIRP at 50 Hz—a reasonable choice at the low frequencies and tissue types discussed here (Reilly 1998). The different procedures and assumptions used by ICES and ICNIRP lead to significantly different BRs.

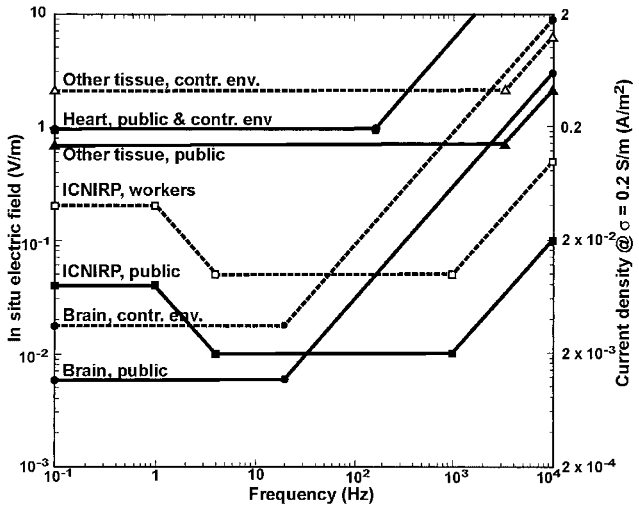

Fig. 1. Basic restrictions of the ICES and ICNIRP. Square symbols apply to ICNIRP, the other symbols to IEEE C95.6. Open symbols apply to the general public; closed symbols to individuals in controlled environments (ICES) or to occupational groups (ICNIRP).

Adverse reaction thresholds (Table 3, items 2 and 3)

ICES defines median thresholds of measurable reactions, which it increases by an adverse reaction factor, F_a, to obtain a median adverse reaction threshold (item 2). To this median value, ICES applies a probability factor, F_p, to arrive at a low-probability ($< 1\%$) adverse reaction threshold of 17.7 mV m^{-1} (item 3).

ICNIRP defines an adverse reaction threshold $J =$ 100 mA m^{-2} to which it applies safety factors to derive BRs. Using $\sigma = 0.2$ S m^{-1}, we compare J to the in situ electric field, $E_i = 500$ mV m^{-1}—a value 28 times that of ICES (item 3).

It is unclear what adverse reaction is supposed by ICNIRP to occur at $J = 100$ mA m^{-2}, and at what probability level. ICNIRP notes changes in cognitive function and phosphene phenomena at 10 mA m^{-2}. It also states: "The severity and the probability of irreversibility of tissue effects becomes greater with chronic exposure to induced current densities above the level of 10 to 100 mA m^{-2}." Considering that ICNIRP viewed the effects in the stated range to be irreversible and increasingly probable, it is unclear why it chose 100 rather than 10 mA m^{-2} as a value to which it would apply its safety factor. The value 100 mA m^{-2} is more than 10 times greater than median thresholds that cause adverse synapse effects at the optimum frequency of 20 Hz (ICES 2002; Sect. 6.1.3), and it is much too small to apply to peripheral nerve or cardiac excitation, for which median thresholds are demonstrated to be about 10 and 20 times greater, or ventricular fibrillation, the only irreversible (usually) effect considered in the two standards, for which thresholds are significantly greater (Reilly 1998).

Probability of adverse reactions (Table 3, item 4)

Using experimental probability distributions of electrostimulation thresholds, ICES defines a median adverse reaction level, to which it applies a reduction factor of one-third to obtain a low probability ($<1\%$) adverse reaction level. In contrast, ICNIRP does not ascribe a probability to the reaction levels it identifies; we do not know, for instance, whether they are medians, low probability levels, or perhaps the lowest adverse reaction levels found in the literature.

Safety factors (Table 3, items 5 and 6)

Both standards include safety factors (F_s) as margins for various uncertainties and unusually sensitive individuals. For ICNIRP, $F_s = 1/10$ and $1/50$ for occupational groups and the general public, respectively; for ICES $F_s = 1$ and $1/3$ for controlled environments and the general public. While a casual reading of the standards might lead one to suppose that because ICNIRP's safety factors are larger than those of ICES, its BRs are more stringent, a careful evaluation shows otherwise. The confusion arises because the levels to which F_s is applied by the two groups are very different.

For the general public, ICES applies $F_s = 1/3$ to the low-probability threshold of 17.7 mV m^{-1}, resulting in a BR of 5.9 mV m^{-1} (item 6). ICES states that the latter protects against adverse synaptic effects in the brain, and that much higher BRs are allowed in the rest of the body (e.g., 0.7 V m^{-1} in most other tissues). In contrast, ICNIRP applies its safety factors to a much higher value of 100 mA m^{-2} ($E = 500$ mV m^{-1}), resulting in a BR of 2 mA m^{-2} ($E = 10$ mV m^{-1}) for the general public.

Fig. 2 illustrates the safety factors used in the two standards. To reduce its complexity, the figure shows limits only for the general public. The reader should be able to visualize a similar figure for occupational/controlled environments. The solid lines are the BRs; the broken lines are reaction levels taken from the standards. To a median adverse reaction level, ICES applies separate reduction factors to account for a low reaction probability ($F_p = 1/3$), and a safety factor ($F_s = 1/3$). In contrast, ICNIRP applies only a safety factor ($F_s = 1/50$) to an adverse reaction level of unspecified probability and effect.

Although ICES and ICNIRP both acknowledge similar thresholds for central nervous system (CNS) interactions of concern, ICNIRP does not apply its safety factor to that low level, but rather to a greatly elevated level, whereas ICES applies its safety factor to that low level. Despite the appearance of more stringent safety factors in ICNIRP, the minimum BRs of ICES below 30 Hz are roughly one-half those of ICNIRP. At those frequencies where ICNIRP has a lower BR, it is due to

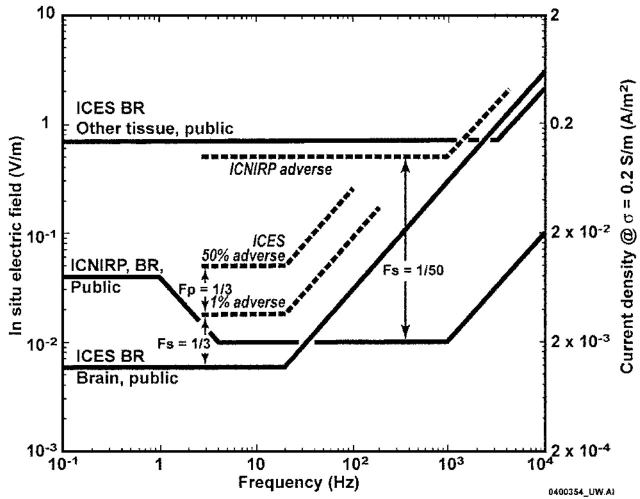

Fig. 2. Basic restrictions of ICES and ICNIRP for the general public with safety factors. Broken lines show assumed adverse reaction levels. F_s = safety factor used by ICES and ICNIRP. F_p = probability factor used by ICES.

different conclusions about the upper inflection frequency and ICES's differentiation of BRs for different tissue types, and not to a difference in safety factors.

Inflection frequencies (Table 3, items 7 and 8)

Thresholds with sinusoidal stimulation have a minimum plateau; above a frequency f_e, they converge to a line that rises in proportion to frequency. ICES finds that f_e and E_o depend substantially on tissue type (Table 1). The lowest rheobase thresholds apply to synapse effects, for which f_e = 20 Hz. In contrast, ICNIRP ascribes f_e = 1,000 Hz to thresholds justified by phosphene effects, but apparently applied to all tissues without distinction. The effect of this choice is large. For instance, ICNIRP's BR at 1,000 Hz would be 50 times greater had they instead chosen f_e = 20 Hz.

As seen in Figs. 1 and 2, ICNIRP applies an upturn in its BRs for frequencies below 4 Hz, but ICES does not. ICES acknowledges that a low frequency upturn in thresholds can be found in experimental literature on nerve stimulation, but it would exist only for an in-situ sinusoidal stimulus initiated near a zero crossing, and not for one initiated near a peak, nor for a square-wave oscillatory stimulus. A further discussion of this issue is given in Reilly (2003) and Reilly and Diamant (2002). ICES states that, by not including the low frequency upturn, its standard is more inclusive of stressful-case waveforms. Fig. 1 shows that this distinction is important only at frequencies below 4 Hz.

Application to different tissue types (Table 3, items 9 and 10)

ICES differentiates BRs for several tissue types, whereas ICNIRP does not. The lowest ICES BRs in Fig. 1 protect against alteration of synaptic processes—a mechanism demonstrated to a have a substantially lower reaction threshold as compared with other electrostimulation effects, albeit only at extremely low frequencies. Among these reactions are visual effects known as phosphenes, which are attributed to alteration of synaptic processes in the retina. Although ICES did not consider phosphenes to be an adverse effect, the E-field level within the retina causing them was regarded as potentially adverse when applied to neurons within the brain.

ICNIRP also uses phosphene data to justify the minimum plateau seen in Fig. 1. However, it does not specify BRs for other tissues in which the phosphene data would obviously not apply. The application of ICNIRP's BRs to all the tissues of the body, rather than only the brain or CNS, has a major impact on the ICNIRP restrictions. Soon after their standard was published, the following clarification was issued by ICNIRP in a set of questions and answers (ICNIRP 1998b) [additions in brackets are provided by this writer].

Q. Is the basic restriction of 10 mA m^{-2} [occupational, 4 Hz–1 kHz] based only on the threshold for acute effects in the CNS [central nervous system], or does it apply to other tissues in the trunk and of the body?

A. The basic restriction of 10 mA m^{-2} is intended to protect against acute exposure effects on CNS tissues in the head [the brain] and the trunk of the body [the spinal cord], with a safety factor of 10. ICNIRP recognizes that this basic restriction may permit higher current densities in tissues other than the CNS under the same exposure conditions.

The question remains: what BR should the ICNIRP user adhere to if the exposure is primarily to tissue other than the CNS? This question might arise in instances of nonuniform exposure, such as when an individual's arms are nearest the source of a field.

The ICNIRP clarification quoted above states that higher current densities could be tolerated in that case, but the standard itself does not specify what that increased level should be.

Synapse restrictions in the brain vs. the spinal cord (Table 3, item 11)

As reprinted above, ICNIRP states that their BRs apply to the spinal cord as well as to the brain. In contrast, ICES avers that the lowest BRs apply to the brain but not the spinal cord due to the lack of evidence that measurable spinal effects occur at exposures below those that cause direct neural excitation (ICES 2002, Sect. 6.1.3). These differing conclusions account for a large difference in BRs in the frequency regime discussed here. For example, the ICES standard for the general public would allow a minimum E-field of 5.9 mV m^{-1} in the brain, but 0.70 V m^{-1} in other tissue (including the spinal cord)—a factor more than 100 times greater. No such distinction is made in ICNIRP.

Magnetohydrodynamic effects (Table 3, item 12)

Magnetohydrodynamic effects result from forces on moving charges (e.g., in the bloodstream) within strong static or nearly static magnetic fields. ICES determined that these effects were not covered by its BRs, and that a separate specification of the in situ magnetic field was required below 10 Hz. Limits for these effects appear in ICNIRP's RLs, but not BRs. If an ICNIRP user exceeds the RL at or near static frequency, he is told to determine whether BRs are also exceeded.

Although ICNIRP's BRs do not offer a corresponding limit that could apply to a static frequency, comparable information was provided in an earlier publication (ICNIRP 1994) in which ICNIRP concluded that fields up to 2 T are not associated with major detrimental effects. ICNIRP applied to that value a safety factor of 1⁄10 and 1⁄50, arriving at chronic-exposure levels of 200 mT and 40 mT for the two groups. ICES, in evaluating some of the same data, found that a field of 1.5 T was associated with adverse reactions in about 50% of tested subjects. The ICES standard applied a factor of 1⁄9 to that for the general public, and 1⁄3 for individuals in the controlled environment, resulting in exposure limits of 500 mT for the controlled environment, and 167 mT for the general public.

The large discrepancy between the ICES and ICNIRP static field exposure limits are, in this case, largely due to large differences in safety factors assumed by the two groups.

MAXIMUM PERMISSIBLE EXPOSURE AND RLS

In addition to BR limits on in situ electrical forces, both groups specify environmental restrictions called "Maximum Permissible Exposure (MPE) Levels" by ICES, and "Reference Levels" (RLs) by ICNIRP.

Magnetic field MPEs and RLs (Table 4, item 1)

An induction model is needed to relate an environmental magnetic field to BRs. ICES uses a homogeneous conductivity ellipsoid fitted to the body or body part in question, for which the maximum induced E-field occurs at the extrema of the semi-minor axes. Based on this model, the broken lines in Fig. 3 plot the B-field needed to induce the median adverse reaction levels in specified tissue. By applying a divisor of 3 (the low-probability factor) to the lower boundary of the broken lines in Fig. 3, we obtain the MPE (upper solid line) for the controlled environment; dividing again by 3 (the safety factor), gives the MPE for the general public (lower solid line).

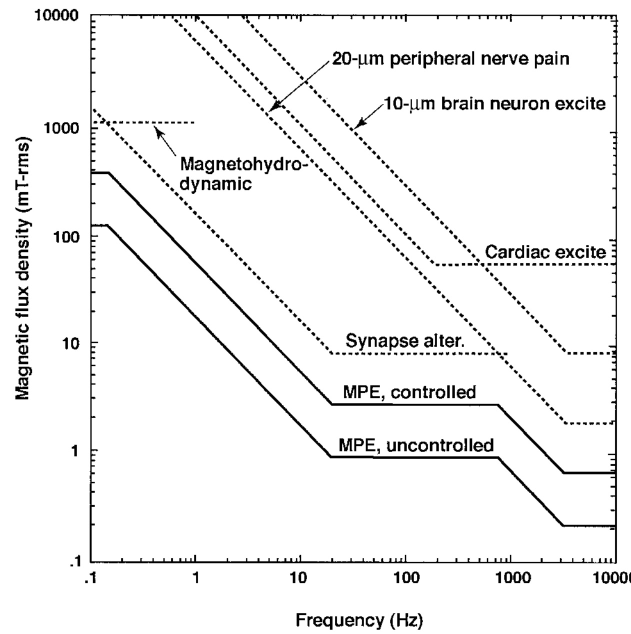

Fig. 3. Median thresholds for adverse stimulation by magnetic fields (broken lines) and ICES recommended maximum permissible exposure (solid) for whole body exposure to spatially constant field [Adapted from figure 11.9 of Reilly (1998)].

ICNIRP used a circular loop induction model. One can infer from stated BRs, RLs, and conductivity at 50 Hz that the circular loop has a radius of 64 cm. Fig. 4 illustrates the ICES model for whole body exposure, and the inferred ICNIRP model. For a given uniform magnetic field perpendicular to the loop, the maximum field induced in the circular loop is 1.7 times greater than in the elliptical loop. As a result, the ICNIRP RLs are lower by a factor of 1.7 than what would have been calculated with the ICES model.

Fig. 5 compares the ICES and ICNIRP MPEs from 0.1–10 kHz. Below 10 Hz they are typically within a factor of 3; above 10 Hz, they increasingly diverge, and maximally diverge by of a factor of 110 at 1000 Hz.

Electric field restrictions (Table 4, item 2)

In ICES, the E-field MPE is not limited primarily by BRs, but rather by the need to avoid unacceptable contact current and spark discharges when a person touches a grounded conductor within a strong field. To appreciate this statement, consider that at 60 Hz it would require an undisturbed environmental E-field of 59 kV m^{-1} to

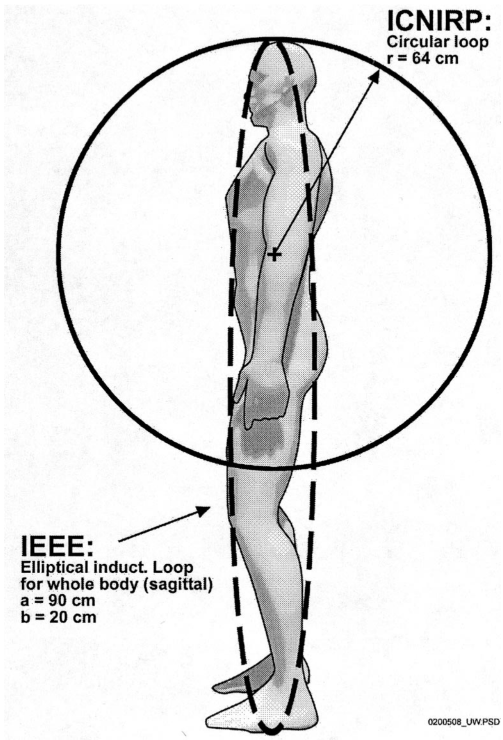

Fig. 4. Comparison of magnetic induction loops used by ICES and ICNIRP.

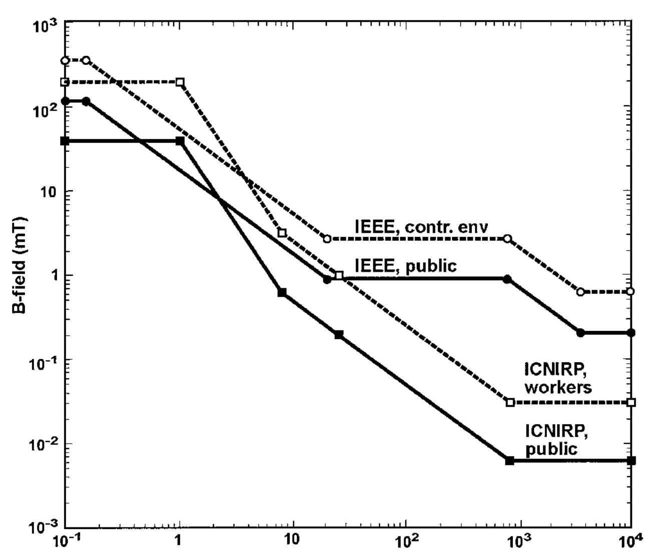

Fig. 5. Magnetic flux density maximum permissible exposures of ICES and ICNIRP.

induce an in situ E-field of 17.1 mV m^{-1} in the brain (Carstensen 1987)—the ICES BR in a controlled environment. Because the environmental E-field is enhanced on body surfaces—18 times, for example, on the head of a standing person, and even more on extended fingertips (Kaune 1981)—parts of the body could be in a state of corona at environmental field levels necessary to induce the BR within the brain.

For a person who is insulated from ground, the contact current when touching a grounded conductor within an electric field is (Reilly 1998):

$$I_s = 9.0 \times 10^{-11} h^2 f E, \tag{3}$$

where h is the person's height (m), f is the frequency of the field (Hz), and E is the electric field (V m^{-1}, vertical polarization). In the ICES standard, h is assumed to be 1.75 m; the limits on I_s are the touch current restrictions given in Table 5 of the standard, namely, 0.5 mA for the general public, and 1.5 mA in the controlled environment.

Fig. 6 shows the E-field MPEs of ICES and ICNIRP. In the ICES standard below 3 kHz, E rises inversely with frequency such that current derived from eqn (3) would be limited to the touch contact current limits of the standard. If the limit derived from eqn (3) were to be extended to arbitrarily low frequencies, the allowable E-field would reach unacceptably large values due to spark discharges that would occur when a person who is insulated from ground touches a grounded conductor. For that reason, E is capped as seen in Fig. 6 so as to limit unacceptable spark discharges.

ICNIRP, on the other hand, states that its E-field RL is intended to limit the current density induced in the neck or trunk to the basic restriction (2 mA m^{-2} for the public). Evaluating eqn (3) with $h = 1.75$ m, $f = 50$ Hz, $E = 5$ kV m^{-1} for the general public, and assuming a neck circumference = 41 cm, we calculate $J = 2$ mA m^{-2}—the ICNIRP BR for the general public. However, a similar calculation for occupational groups (for which $E = 10$ kV m^{-1} is allowed), yields $J = 4$ mA m^{-2}—which is below the allowed occupational BR by a factor of 2.5. ICNIRP does not provide justification for using a lower BR for the occupational group's E-field RL. The inflection frequencies chosen by ICNIRP are 820 and 3,000 Hz for occupational groups and the general public, respectively; the rationale for this choice is not provided in the standard.

While the ICNIRP E-field RLs are intended to limit J, they also, in effect, limit the current contacted by a person who touches a grounded conductor within the field. With $h = 1.75$, the limit is 69 and 138 μA for the general public and occupational groups, respectively, according to eqn (3) for $f = 25$–3,000 Hz, and 25–820 Hz. These limits are well below the ICNIRP contact current restrictions of 0.5 and 1.0 mA for the general public and occupational groups, respectively (Table 8 of the ICNIRP standard).

For frequencies from 1–368 Hz, the ICES E-field limit is 5 kV m^{-1} for the public. However, within power

Table 5. Example basic restrictions of ICES and ICNIRP.

	General public					
	Brain			Other tissue		
Freq. (Hz)	ICES (V/m)	ICNIRP[a] (V/m)	Ratio ICES/ ICNIRP	ICES[b] (V/m)	ICNIRP[a] (V/m)	Ratio ICES/ ICNIRP
20	0.0059	0.01	0.59	0.70	0.01	70
60	0.018	0.01	1.8	0.70	0.01	70
1,000	0.29	0.01	29	0.70	0.01	70
3,000	0.88	0.03	29	0.70	0.03	23
	Controlled environment					
20	0.018	0.05	0.36	2.10	0.05	42
60	0.053	0.05	1.1	2.10	0.05	42
1,000	0.89	0.05	18	2.10	0.05	42
3,000	2.7	0.15	18	2.10	0.15	14

[a] ICNIRP current density converted to E-field based on $\sigma = 0.2$ S/m.
[b] ICES exceptions for heart, hands, feet, wrists, and ankles.

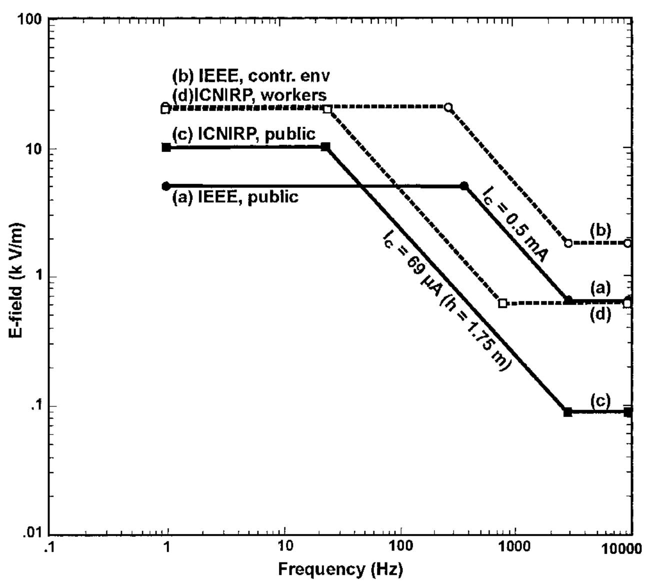

Fig. 6. Maximum permissible exposure levels to electric fields in standards of ICES and ICNIRP. In ICES, MPEs are selected so that the current conducted by a person (h = 1.75 m) equals the allowable touch current (Table 5 of the standard), but with a cap that limits the intensity of spark discharges. In the ICES standard, both the BR and the E-field MPE must be satisfied.

line rights-of-way (ROWs), the limit is raised to 10 kV m^{-1}, with the explanation that power line ROWs are quasi-controlled environments. In contrast, ICNIRP limits exposure to the general public in power line ROWs to 5 and 4.2 kV m^{-1} at 50 and 60 Hz, respectively, but allows exposures up to 10 kV m^{-1} below 25 Hz.

Joint BR and MPE for E-field exposure (Table 4, item 5)

Both ICNIRP and ICES recognize that BRs alone are inadequate to protect against adverse reactions in strong electric field environments. Induction of an electric field (or current density) within the body equal to ICNIRP or ICES BRs would require a field intensity that would result in painful spark discharges when a person insulated from ground touches a grounded object. That is why both ICNIRP and ICES place caps on the MPE/RL. Consequently, to adhere to BRs and at the same time to avoid painful spark discharges, the standard should require adherence to both the BRs and the MPE/RL. This joint requirement is clearly stated in the ICES, but not in the ICNIRP standard. However, ICNIRP provides the following footnote to its table of electric and magnetic field RLs (Tables 6 and 7 of ICNIRP 1998a): "Provided the basic restrictions are met and adverse indirect effects can be excluded, field strength values can be exceeded." ICNIRP does not explain how to determine whether adverse indirect effects can be excluded, or, for the general public, by how much the E-field limit can be increased. For occupational groups, ICNIRP states: "For the specific case for occupational exposures at frequencies up to 100 kHz, the derived electric fields can be increased by a factor of 2 under conditions in which adverse indirect effects from contact with electrically charged conductors can be excluded."

SUMMARY AND CONCLUSION

Tables 5 and 6 compare the ICES and ICNIRP standards at selected frequencies in the spectrum covered by IEEE C95.6. The column labeled ICES/ICNIRP lists the ratio of the limits of ICES divided by those of ICNIRP at the indicated frequencies. For BRs, (Table 5) the greatest ratio in the brain occurs at and above 1000 Hz, mainly because of differences in the assumed value of f_e. For "other tissue," the ratio is 70 over a broad range

Table 6. Example MPEs and RLs of ICES and ICNIRP (whole body exposure).

	General public					
	B-field			E-field		
Freq. (Hz)	ICES (mT)	ICNIRP (mT)	Ratio ICES/ ICNIRP	ICES (V/m)	ICNIRP (V/m)	Ratio ICES/ ICNIRP
20	0.9	0.25	3.6	5,000	10,000	0.5
60	0.90	0.083	11	5,000[a]	4,170	1.2[a]
				10,000[a]		2.4[a]
1,000	0.69	0.0063	110	1,840	250	7.4
3,000	0.23	0.0063	37	614	83	7.4
Controlled environment						
20	2.71	1.25	2.2	20,000	20,000	1.0
60	2.71	0.417	6.5	20,000	8,330	2.4
1,000	2.06	0.031	67	5,440	610	8.9
3,000	0.68	0.031	22	1,813	610	3.0

[a] E-field exception within transmission line ROW = 10,000 V/m (general public).

of frequencies, mainly because ICES distinguishes BRs for different tissue types, but ICNIRP does not.

For MPEs and RLs (Table 6), the maximum ratio of 110 occurs at 1,000 Hz; this ratio exceeds that of the BRs because of differences in magnetic field induction models used by the two groups.

Tables 3 and 4 summarize the main technical reasons for the differences in limits determined by ICES and ICNIRP. These tables should help define the issues that must be clarified to achieve harmonization between the two standards.

The following technical factors are the major ones responsible for the divergent standards of ICES and ICNIRP.

Basic restrictions

1. Differences in the upper transition frequency (f_e) for adverse electrostimulation of the CNS;
2. Threshold for adverse CNS effects;
3. Inclusion of the spinal cord along with the brain for the lowest BRs;
4. Application of retina effects in the brain/CNS;
5. Different BRs for different exposed tissue; and
6. Definition of probability ranks for adverse effects.

Environmental limits (MPEs and RLs)

1. Physical model for magnetic induction;
2. Safety factors necessary for static or near-static magnetic field exposure;
3. E-field cap at the lowest frequencies;
4. Allowed E-field induced current without contact with other objects at frequencies below the E-field cap; and
5. Transition frequencies for E-field exposure.

To resolve the differences in the standards of the two groups, I recommend that research priority be given to the factors mentioned above. With adequate attention to the technical factors mentioned here, it should be possible to arrive at a single advisory consensus that can be used internationally by standard-setting agencies.

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