Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of	)	
	)	
Reassessment of Federal Communications Commission Radiofrequency Exposure Limits and Policies	)	ET Docket No. 13-84
	)	
Proposed Changes in the Commission's Rules Regarding Human Exposure to Radiofrequency Electromagnetic Fields	)	ET Docket No. 03-137
	)	

REPLY OF THE INTERNATIONAL COMMITTEE ON ELECTROMAGNETIC SAFETY (ICES) OF THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC. (IEEE)

This document solely represents the views of ICES and does not necessarily represent a position of either the IEEE or the IEEE Standards Association (IEEE-SA).

Dr. Ralf Bodemann
Chairman of the International Committee on Electromagnetic Safety
Institute of Electrical and Electronics Engineers, Inc.
ralf.bodemann@ieee.org
+49 173 856 1184

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SUMMARY

Pursuant to Section 1.405 of the Federal Communications Commission's (FCC's) Rules,[1] the International Committee on Electromagnetic Safety (ICES) of the Institute of Electrical and Electronics Engineers (IEEE) hereby replies to the submittals concerning *Further Notice of Proposed Rule Making* (FNPRM) and *Notice of Inquiry (*NOI) issued by the Commission in the above-captioned proceeding.[2] This document replies to the joint submittal by Momentum Dynamics (MD) Corporation and Oak Ridge National Laboratory (ORNL), dated September 3, 2013.

The MD/ORNL statement addresses the questions: (1) Should the FCC extend its oversight to frequencies below 100 kHz? (2) If yes, what international organization's standard/guidelines should the FCC adopt? Based on the information contained in the Appendix to their submittal, MD/ORNL recommends:

> "... should the Commission decide to adopt limits below 100 kHz, the limits should be based upon the latest relevant IEEE Standards, C95.1-2005, C95.6-2002, and C95.7-2005."

ICES will not address question (1). Concerning question (2), for frequencies below 100 kHz, ICES recommends that the FCC adopt the maximum permissible exposure (MPE) values and basic restrictions (BR) of IEEE Standards C95.1-2005 and C95.6-2002 (reaffirmed by the IEEE Standards Association Standards Board in 2007 following ICES reaffirmation balloting). This

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1 47 C.F.R. §1.405.

2 *See* Reassessment of Federal Communications Commission Radiofrequency Exposure Limits and Policies, in ET Docket No. 13-84, *and* Proposed Changes in the Commission's Rules Regarding Human Exposure to Radiofrequency Electromagnetic Fields, in ET Docket No. 03-137, FCC 13-39 (Released: March 29, 2013).

recommendation is in concert with the position of MD/ORNL. This reply supplements the information contained in the MD/ORNL submittal, providing further backing for adoption of the IEEE limits below 100 kHz if the FCC decides to set exposure limits at those frequencies. A discussion supporting adoption of the IEEE limits at higher frequencies is provided in our previous submission to the FCC on 3 September, 2013.

I. DISCUSSION

Two existing IEEE standards collectively define limits on human exposure to electromagnetic fields and electric currents over the spectrum from 0 Hz to 300 GHz: C95.6-2002 (from 0 Hz to 3 kHz) and C95.1-2005 (from 3 kHz to 300 GHz).[3] Various applications of electrical technology create emissions within this broad frequency range. The 3 September 2013 submittal by IEEE ICES urges the FCC to adopt the limits in the IEEE standards at frequencies related to broadcast and wireless industries.[4] With this reply, ICES further recommends that if the FCC extends its oversight to frequencies below 100 kHz, the FCC adopt the MPEs and BRs in the IEEE standards with respect to frequencies below 100 kHz.

The intent of the limits in these IEEE standards is to protect against established adverse human reactions from exposure to electric, magnetic and electromagnetic fields in the frequency range 0 Hz to 300 GHz. Many applications of electrical energy could potentially create more than trivial emissions below 100 kHz. One such possible application is anti-theft technology, which is common in many retail facilities. Another example is the switched gradient field used in MRI scanners. Although the IEEE standards state that the limits are not intended to apply to patient exposure during medical procedures, that would not preclude application to the practitioners who administer such procedures. The FDA and the IEC both set MRI limits for exposure of patients, but not for the personnel involved in those procedures. Other low frequency applications are on the drawing board, such as the wireless charging systems addressed in the MD/ORNL position to which this document replies.

The Annex attached herewith provides rationale for the FCC adoption of the limits in IEEE Standards C95.6-2002 and IEEE C95.1-2005.

II. ICES Position

For the reasons summarized below, ICES supports the recommendation of MD/ORNL that if the FCC concludes that setting exposure limits below 100 kHz is beneficial or necessary, it should adopt the limits in IEEE C95.6-2002 (reaffirmed in 2007) and C95.1-2005. Adoption of both IEEE C95.6 and C.95.1 would provide coverage of the full spectrum from 0 Hz to 300 GHz with science-based standards developed by a single, highly qualified and representative body through a thorough,

[3] ICES is in the process of reviewing and updating its standards, and combining IEEE Standards C95.1-2005 and C95.6-2002 (reaffirmed in 2007) into a single document.

[4] Comments of The International Committee on Electromagnetic Safety (ICES) of The Institute of Electrical and Electronics Engineers, Inc. (IEEE), submitted in response to Notice of Inquiry issued by the Federal Communication Commission, dated 30 August, 2013, and submitted on September 3, 2013.

open and transparent process.[5]

For example, the limits in IEEE C95.6 are based on clearly defined scientific principles connecting experimental data and theoretical models of human reactions. That standard provides tissue-specific limits in a self-consistent manner. These limits are developed through consultation with a broad base of constituencies that include a wide range of points of view.

IEEE standards are developed with oversight by the IEEE Standard Association under the principles of transparency and due process afforded to all.[6] The IEEE standard development process is further governed by principles of balance, representation across the social spectrum of concerns over safe exposure, and fair consideration of all competing viewpoints, research, and data. The IEEE standards define safety levels with respect to human exposure to electromagnetic fields that are based on the best available science and engineering and, as such, they are scientifically defensible. The subcommittee that developed IEEE C95.6 has a broad range of participation by over 68 experts in engineering, biology, medicine, measurements and safety programs. The committee's balanced membership consists of members of the government, military, academia, and industry.

Although ICNIRP (another organization mentioned by the FCC in its NOI) has defined limits with respect to the safe exposure to electromagnetic fields, ICES submits, for reasons summarized below, that the ICES standards have many strengths over the ICNIRP 2010 guidelines:

(1) **Objectives.** It is clearly stated in IEEE Standards C95.6-2002 and C95.1-2005 that, in the absence of established evidence for chronic effects of low-level, long-term exposure below the limits in these standards, their objectives are to avoid adverse biological effects, which are defined in 4.3 of IEEE C95.6.

(**2)** **Data trail.** The IEEE standards provide a clear path from experimental adverse effect thresholds and theoretical principles to the limits of the standards.

(3) **Safety/reduction factors**. The rationale behind reduction factors is made clear in the IEEE standards, and separate components of those factors are identified.

(4) **Probability models and treatment**. The probabilities associated with reaction thresholds, including the limit values, are made clear in the IEEE standards.

(5) **Exposure of the limbs**. The IEEE standards provide separate limits for exposure of the limbs.

(**6)** **Definition of exposed populations.** The IEEE standards clearly define the two categories of exposed populations in a rational manner.

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[5] Consistent with Office of Management and Budget (OMB) Circular A-119 Revised, "Federal Participation in the Development and Use of Voluntary Consensus Standards and in Conformity Assessment Activities," (Feb., 1998).

[6] One of the hallmarks of IEEE's process is its inclusion of all materially interested parties, along with transparency, due process, documentation, balancing and consideration of all interests, and appeal rights. In addition, IEEE ICES represents a large international contingency: the main committee of ICES, TC95, has approximately 122 members, including members of the Federal RF Interagency Working Group (FCC, FDA, NIOSH and OSHA). Over one-third of the members are from outside the U.S., with 22 members from important Far East countries (such as China, Korea, and Japan). The representation of various viewpoints allows IEEE ICES to consider and address issues with implementation that may not be considered in a less inclusive process.

(7) Induction Models. In the IEEE standard, an artifact-free model is used to derive the MPE values from the basic restrictions.

(8) CNS limits below 20 Hz. The IEEE standards provide central nervous system (CNS) limits at very low frequencies (< 20 Hz) that take into account biophysical responses that might occur with realistic exposure waveforms.

(9) Environmental E-field limits – consistency. The MPE values for electric fields are consistent with contact current limits elsewhere in the two IEEE standards.

(10) Environmental E-field limits in power line ROWs. Relaxed limits for the general public within power line rights of way (ROWs) are included in IEEE C95.6-2002.

ICES believes its standards best define exposure levels that (1) are sufficiently low, and with an adequate margin of safety, to protect against demonstrated adverse health effects in humans and (2) are not unnecessarily low in light of the body of available scientific evidence. The FCC's NOI acknowledges that rulemaking must include weighing relative costs and benefits. *See, e.g.*, NOI 229. Thus, the FCC should avoid adoption of limits that unnecessarily restrict technology or increase costs by requiring compliance with unjustifiably stringent limitations. For example, ICNIRP's 1998 low frequency limits adversely affected several applications, e.g., MRI, which led ICNIRP to relax its guidelines in 2010 without any adverse effect on safety.

If the FCC decides to regulate exposures in the 0-100 kHz spectrum, it must avoid the possibility of erring in two ways: (1) adoption of highly restrictive limits at the risk of unnecessarily constraining technology development, and (2) adoption of insufficiently restrictive limits that possibly put the health and safety of the public at risk. As noted, ICES believes that adoption of its standards avoids this dilemma: its standards fairly balance the need to protect the public from scientifically established mechanisms of biological effects in humans without being unnecessary stringent in light of scientific evidence. Further comparison of the IEEE ICES standards with the applicable ICNIRP 2010 guidelines is provided in the Annex.[7]

For deeper inspection of such conflicts, ICES recommends possible consultation with additional resources to assist in evaluating the technical rationale for selection of limits in the 0 Hz - 100 kHz region. Such agencies or bodies might include the National Council on Radiation Protection and Measurements (NCRP), which has historically been involved in evaluating public health implications of electromagnetic field exposure; the Federal RF Interagency Working Group; and the Committee on Man and Radiation (COMAR).[8]

[7] The Annex to this letter is based on a paper prepared by J.P. Reilly for Momentum Dynamics and submitted to the FCC as an Appendix to the MD/ORNL comments dated 2 September 2013. The Annex hereto was prepared by J.P. Reilly with significant review and input by ICES. The Annex supplements, expands on, and clarifies information in J.P. Reilly's September 2 paper, prepared for Momentum Dynamics, but does not change or contradict the conclusions in that paper. The Annex hereto represents the collective position of ICES.

[8] COMAR is a Technical Committee of the Engineering in Medicine and Biology Society (EMBS) of the Institute of Electrical and Electronics Engineers (IEEE). COMAR's primary area of interest is biological effects of non-ionizing electromagnetic radiation.

III. <u>CONCLUSION</u>

If the Commission elects to extend its oversight to frequencies below 100 kHz, ICES concurs with the recommendation of MD/ORNL that the FCC adopt the limits in IEEE Standards C95.6-2002 (reaffirmed in 2007) and C95.1-2005 across the spectrum. The two standards are being updated based on an evaluation of the scientific evidence and developments since the two standards were last approved or reaffirmed, and, if finally approved through the IEEE's rigorous and open balloting and approval process, will be published as a single document that covers the full spectrum from 0 Hz to 300 GHz.

Respectfully submitted,

Dr. Ralf Bodemann
Chairman of the International Committee on Electromagnetic Safety
Institute of Electrical and Electronics Engineers, Inc.
ralf.bodemann@ieee.org
+491738561184

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Annex

HUMAN EXPOSURE STANDARDS IN THE FREQUENCY RANGE 1 Hz TO 100 kHz: THE CASE FOR ADOPTION OF THE IEEE STANDARD.

J. Patrick Reilly[1]

Abstract—Differences between IEEE C95 Standards (C95.6-2002 and C95.1-2005) in the low-frequency (1 Hz – 100 kHz) and the ICNIRP-2010 guidelines appear across the frequency spectrum. Factors accounting for lack of convergence include: differences between the IEEE standards and the ICNIRP guidelines with respect to: biological induction models; stated objectives; data trail from experimentally derived thresholds through physical and biological principles; selection and justification of safety/reduction factors; use of probability models; compliance standards for the limbs as distinct from the whole body; defined population categories; strategies for central nervous system protection below 20 Hz; correspondence of environmental electric field limits with contact currents. This paper discusses these factors, and makes the case for adoption of the limits in the IEEE standards.

Key words: safety standards; EMF exposure; nonionizing; electromagnetic fields; health effects; regulatory guides.

INTRODUCTION

Standards and guidelines on human exposure to electric, magnetic and electromagnetic fields and electric currents have been issued by two international organizations: the Institute of Electrical and Electronics Engineers, Inc. (IEEE—headquartered in New York, USA), and the International Commission on Non- Ionizing Radiation Protection (ICNIRP—headquartered in Munich, Germany).[2] The IEEE committee responsible for development of standards for electromagnetic exposure is known as the International Committee on Electromagnetic Safety (ICES). The World Health Organization in its fact sheet #193 has recognized both organizations in developing exposure guidelines for workers and for the general public.[3]

Both the IEEE C95 standards and the ICNIRP guidelines cover the frequency range of 0 Hz (static) to 300 GHz. This document focuses on the frequency regime from 1 Hz to 100 kHz, where the dominant mechanism of biological interaction is *electrostimulation*—the excitation of nerve and muscle by applied electrical energy. For

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[1] Metatec Associates. 12516 Davan Dr., Silver Spring, MD 20904. For correspondence, contact the author at that address, or email at jpreilly@erols.com.

[2] The IEEE considers its limits as constituting a "voluntary standard;" ICNIRP considers its limits as "Guidelines." Neither organization has enforcement power. Adoption and enforcement of either standard is at the discretion of adopting agencies, whether governmental, or other.

[3] (http://www.who.int/mediacentre/factsheets/fs193/en/index.html).

frequencies above 100 kHz, the dominant mechanism is typically a thermal one[4] (Reilly, 1998, pp. 265-269).

IEEE limits cover the frequency range 0 Hz to 3 kHz in IEEE Standard C95.6-2002 (IEEE, 2002), and the frequency range 3 kHz to 100 kHz in IEEE Standard C95.1-2005 (IEEE, 2005). Principles of electrostimulation forming the basis of IEEE C95.6 and C95.1 are found in (Reilly, 1998) and updated in (Reilly & Diamant, 2011).

In 1998 ICNIRP published exposure guidelines for the frequency range 0 Hz to 300 GHz (ICNIRP, 1998). Sizable differences between the low frequency limits of IEEE C95.6-2002 and ICNIRP-1998 were evident – at some frequencies differences were as great as a factor of 100, despite the fact that both organizations espoused the same objectives and reviewed essentially the same literature (Reilly, 2005).

Technical factors responsible for these large discrepancies include: *in situ* metrics; interpretation of published literature and theoretical principles; selection of transition frequencies at which thresholds obeyed different power laws; differentiation of limits for different tissues of the body; induction model; treatment of “safety factors;” and consistency issues in environmental electric field limits (Reilly, 2005).

ICNIRP’s revised guidelines, published in 2010, were more closely aligned with IEEE C95.6-2002 due to changes with respect to: inclusion of an *in situ* metric using the induced electric field; revision of transition frequencies; differentiation of central nervous system (CNS) and other tissue; substitution of an improved induction model; and reconsideration of published literature and theoretical principles. Despite the substantial reduction of differences, significant discrepancies between the two standards still remain at frequencies below 100 kHz.

COMPARISON OF IEEE STANDARDS WITH ICNIRP GUIDELINES FROM 1 Hz – 100 kHz

IEEE standards and ICNIRP 2010 guidelines express both *in situ* and environmental exposure limits. The *in situ* limits are termed *Basic Restrictions* (BRs) by both organizations; the environmental limits are called *Maximum Permissible Exposure* (MPE) by IEEE, and *Reference Levels* (RLs) by ICNIRP. It is typically much easier to determine compliance with MPEs than BRs. Compliance with the MPEs ensures that the BRs are satisfied. However, exceedance of an MPE or RL does not necessarily mean a BR is exceeded. In such cases, a user has the option of demonstrating compliance with the BRs through measurement or calculation.

Both organizations provide two tiers of limits – one tier is identified as the General Public; the other is identified as *Individuals in Controlled Environments* by IEEE, and *Occupational Exposure* by ICNIRP.

[4] For pulsed electrostimulation, particularly of low duty factor, the dominance of electro-stimulation vs. heating effects can extend well into megahertz frequencies (Reilly, 1998, pp. 134-141). This paper focuses on continuous sinusoidal stimulus waveforms, where the dividing line between electrostimulation and thermal effects is at about 100 kHz (Reilly, 1998, pp. 265-269).

Table 1 lists IEEE BRs, which are differentiated among the tissue types as: brain; heart; hands, wrists, feet and ankles; and "other tissue."[5] As seen in Table 2, ICNIRP differentiates between only two tissue types: the brain, and "other."

Table 3 lists the IEEE MPEs. In this case, allowable exposure of the head and torso (effectively, "whole-body" exposure) is differentiated from the limbs. However, ICNIRP makes no such distinction (Table 4). Tables 5 and 6 list the IEEE environmental E-field MPEs and ICNIRP RLs, respectively.

Figure 1 compares the IEEE and ICNIRP BRs. At frequencies above a few hertz, the IEEE limits for the brain are lower than those of ICNIRP, typically by a factor of 2 – 3. As the frequency drops below10 Hz, IEEE limits become increasingly conservative relative to ICNIRP. For peripheral nerve stimulation (PNS), the IEEE limits exceed those of ICNIRP by a factor of about 2.

Figure 2 compares the environmental magnetic field limits of the two organizations. Excepting exposure of the limbs, the IEEE MPE values assume exposure of the head and torso. Consequently, the MPEs below 759 Hz would be dominated by the most sensitive tissue (those of the CNS where synaptic function can be affected). The IEEE limits typically exceed those of ICNIRP by factors of about 3 – 5 over most of the frequency spectrum. For exposure of the limbs but insignificant exposure of the head and torso at frequencies above 1000 Hz, IEEE limits exceed those of ICNIRP by a factor of about 10 or more. Below 1000 Hz, IEEE MPEs for the limbs exceed the RLs of ICNIRP by a factor exceeding 100. The reason for such a large discrepancy is that extremity exposure does not include the brain, which is much more sensitive to electrostimulation than other tissue at frequencies below 1000 Hz,[6] and the magnetic induction areas of the limbs are smaller than those of the head and torso (C95.6, Annex B).[7]

THE CASE FOR ADOPTION OF THE IEEE MPES AND BASIC RESTRICTIONS

Although the 2010 revision of the ICNIRP guidelines are less stringent than its 1998 predecessor for frequencies below 100 kHz, significant differences between the IEEE and ICNIRP limits in that frequency domain remain. The discussion below addresses these discrepancies and makes a case for preference of the limits in the IEEE Standards in the frequency regime below 100 kHz.

The rationale for the IEEE electrostimulation limits is fully developed in IEEE C95.6-2002 (Sect. 6). Although that document provides limits only up 3 kHz, the rationale is equally applicable to electrostimulation at much higher frequencies, including the upper limit of 100 kHz discussed here (C95.1, Sect. C.2; Reilly, 1998, pp. 134-141).

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[5] In some cases the units or formats of the original data expressed in Tables 1 – 4 have been converted to other forms for clarity and consistency.

[6] Such CNS sensitivity is due to the effects of the induced *in situ* electric field on synaptic processes within the brain (Reilly, 1998, pp. 387-393; Reilly & Diamant, pp. 147-150).

[7] For brevity, hereafter the citation IEEE C95.6-2002 is cited simply as *C95.6*, and ICNIRP-2010 is cited simply as *ICNIRP*.

Table 10 of IEEE C95.6-2002 provides an overview of the derivation of IEEE BRs, in which numerical data are presented on: the median thresholds of just-noticeable reaction; the adverse reaction levels; a factor to convert median thresholds to low probability reaction thresholds; safety factors; and the final BR value. The text provides the justification, including experimental references. Figure 1 of C95.6 provides an overview of the derivation of MPEs, and Appendix B describes the mathematical induction model used to derive the MPEs from the BRs.

Objective and purpose of the standards and guidelines

Both organizations state the objective to protect against established adverse health effects of an acute nature (C95.6, Sect. 4.3; ICNIRP, p. 818, col. 2).

In the absence of established evidence for chronic effects of low-level long-term exposure, the IEEE standards clearly identify adverse effects in this frequency regime to include aversive or painful electrostimulation (C95.6, Sect. 4.3), and provides a basis for its values with a complete explanation of the relevant principles and experiments (C95.6, Sect. 6).

In contrast, although ICNIRP states its purpose is to protect all persons against adverse effects (ICNIRP, p. 818, col. 1), specific adverse reactions are not identified. For example, in discussing protection afforded by the RLs, ICNIRP refers to “PNS effects” (p. 828, col. 1) but does not specify whether these effects are perception, discomfort, pain, motor twitch, limits of tolerance, or something else, nor does it reveal percentile ranks associated with the quoted data and derived limits. Consequently, one cannot properly evaluate whether the protection afforded in that standard is adequate, excessive, or overly permissive.

Data trail leading to BR and MPE limits

The IEEE standards provide a complete data and computational trail leading from experimental and theoretical sources to the actual limits, with every step and assumption clearly and numerically defined (Sect. 6). Consequently, it is possible for someone to follow the IEEE reasoning, to duplicate or repudiate those results, or to determine the consequences if new data were to become available or if other assumptions were made.

This is not the case in the ICNIRP guidelines. In general, the reader is not given the information with which to determine how ICNIRP determined the BRs. ICNIRP discusses various publications on electrostimulation, but the connection between the ICNIRP limits and the cited literature is not evident.

For instance ICNIRP (2010, p. 825, col.1) states that with exposure to the head and body in controlled environments, the BR of 800 mV/m includes a “reduction factor” of 5 below a putative stimulation threshold of 4 V/m. Such a statement begs the questions: To what waveform does the experimentally derived threshold 4 V/m apply? How did ICNIRP extrapolate this result to sinusoidal exposure at frequencies outside the specified range in Table 2, and what is the justification for such extrapolation? Is the 4 V/m value the threshold of perception as the statement implies? If so, how can this be understood as an adverse reaction? What probability rank among the population does 4 V/m apply to – 50%? 1%? Is this the lowest observable effect level or the lowest observable adverse effects level? What probability rank would apply at the BR level? Is 4 V/m a peak or an *RMS* value, and how does this comport with experimental values?

Safety/Reduction factors

To develop an exposure limit, a "reduction" or "safety" factor is typically applied to what is considered an adverse effects level. IEEE ICES and ICNIRP adhere to different philosophies in applying such margins.

In developing its BRs, IEEE ICES identifies a population median adverse reaction level, as noted in Table 10 of IEEE C95.6-2002, column D,[8] and C95.6, Sect. 6.9.1.1. That value is converted to a low probability reaction level (i.e., no more than conservatively determined 1% or less of persons would find the stimulus painful) by reducing the median value by a Probability Factor, F_P (Table 10 of IEEE C95.6-2002, column E). That value is further reduced by applying a "Safety Factor," F_S (column F), which accounts for various uncertainties. The inverse of the product $F_P F_S$ might be compared with what is called a "Reduction Factor" by ICNIRP, or a "Safety Factor" in IEEE C95.1-2005 at higher frequencies.[9] For most of the effects under consideration, the product $F_P F_S = 1/3$ for the controlled environment (equivalent to "Occupational Exposure" in ICNIRP) and 1/9 for the general public (where the factors are multipliers).

ICNIRP cites "Reduction Factors" (divisors), including 5 for the general public BR of the head, and 10 for the rest of the body (p. 825, col. 2). An additional reduction factor of 3 is applied for the General Public RL (p. 827, col. 2). When the ICNIRP BR and RL safety factors are combined, the total reduction factor is 15 for the head, and 30 for the rest of the body. The ICNIRP guidelines do not provide the physiological or statistical bases for these reductions and do not attend to the implications of not applying a reduction factor for the adverse effects of occupational exposures. Consequently, the rationale for ICNIRP's limits is unclear.

Probability models

Electrostimulation thresholds vary from person to person. Such intersubject variability is found to be considerably greater than variations in a single subject measured repeatedly over time (Reilly, 1998, pp 282-290). Intersubject variations usually fit well

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[8] The Median Adverse Reaction Levels in IEEE C95.6-2002 (products of columns C and D of Table 10) are derived from a just noticeable threshold by applying a multiplier that depends on the particular tissue under consideration (column D) (C95.6, Sect. 6.2). For peripheral nerve stimulation (PNS) a multiplier of 1.45 converts the perception threshold to a pain threshold (C95.6, Sect. 6.2). For central nerve stimulation, the just noticeable reaction is considered adverse, i.e., $F_S = 1$.

[9] In IEEE C95.6-2002, the product $F_P F_S = (1/3) \times (1/3) = 1/9$ in most cases for the general public, and is 1/3 for the controlled environment. To compare these reduction factors to the "Safety Factor" applied to specific absorption rates (SAR) at higher frequencies, note that the SAR safety factor is applicable to the square of the *in situ* field, whereas the product $F_P F_S$ is applied to the magnitude of the field. One would have to square the product $F_P F_S$ to compare it with the inverse of the SAR safety factor.

to a lognormal statistical model (Reilly, 1998, pp. 282-290; Reilly & Diamant, 2011, pp. 111-114), especially for probability ranks at and below 50%.

IEEE standards incorporate probability factors to account for such statistical characteristics (C95.6, Sect. 6.8). Probability levels associated with reaction thresholds and the limits of the standard are defined (C95.6, Table 10).

ICNIRP does not refer to intersubject variations. It is unclear what phenomena are included in its "Reduction Factors." It does not discuss in meaningful depth probabilities associated with reaction thresholds that are mentioned throughout its guidelines.

Separate magnetic field limits for exposure of the limbs

The MPE values in IEEE Standards C95.1-2005 and C95.6-2002 (Tables 2 and 3 in both standards) separately specify limits for exposure of the limbs to allow for nonuniform exposures in which the limbs may be preferentially exposed, but with insignificant exposure to the head and torso. An example would be the case of an attendant in an MRI examination who places his/her hands and arms into the core, possibly to minister to the patient, but with very little exposure to his/her head or torso.[10] The exclusion of the examiner's head from maximal exposure is particularly significant, since the exposure limits for the brain at low frequencies are particularly low (C95.6, Sect. 6.1.3). It would be overly conservative to require an examiner to comply with exposure limits for the brain, when only his/her arms are exposed. The MPEs in the IEEE standards for the limbs are greater than whole body values, not only because the brain is excluded, but also because the magnetic cross sectional induction area of the limbs is much smaller than that of the head and torso (C95.6, Annex. B).

ICNIRP has no separate provisions for exposure of the limbs. Consequently, the MPE values of that standard may be unnecessarily restrictive in cases where the limbs are primarily exposed.

Definition of exposed populations

IEEE C95.6-2002 provides limits for two categories of exposed individuals:

> *General Public*: All individuals who may experience exposure, except those in controlled environments (Sect. 3.1.28).
>
> *Controlled Environment:* An area that is 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 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 health effects (Sect. 3.1.15).

Accordingly, persons in occupational settings and those in controlled environments are not necessarily the same. For instance, in the IEEE standards an office worker or a

[10] The IEEE standard does not apply to patients undergoing medical procedures (C95.6, Sect. 1.1), but it would apply to practitioners, who would be considered as persons within a controlled environment.

grounds-keeper in a facility with an electromagnetic field source would not be considered subject to the Controlled Environment limits unless special conditions were met (C95.6, Sect. 4.1 & 3.1.15).

ICNIRP (pp. 834 – 835) recognizes two categories: *General Public,* and *Occupational Exposure*, which are defined as:

> *General Public*: ... the entire population. It includes individuals of all ages and of varying health status, and this will include particularly vulnerable groups or individuals such as the frail, elderly, pregnant workers, babies and young children.
>
> *Occupational Exposure:* All exposure to EMF experienced by individuals as a result of performing their regular or assigned job activities.

The ICNIRP definition of *Occupational Exposure* includes individuals who might be considered members of the general public in the IEEE standard. As a result, the ICNIRP guidelines could allow untrained or naive workers to experience exposure at levels intended for occupational groups having such training or knowledge, thereby removing the added safety margin afforded to the general public by virtue of their naivety or lack of training.

Induction models

To derive MPEs from the BRs, IEEE C95.6-2002 uses an ellipsoidal uniform conductivity (EUC) model to fit the body or body part under consideration. The EUC model supports an analytic solution to the induced electric field (E-field) at any point within the ellipsoidal volume with arbitrarily high precision (C95.6, Annex B; Reilly, 1998, pp. 363-366).

ICNIRP-2010 uses a Finite Difference Time Domain (FDTD) detailed anatomical induction model.[11] FDTD models allow one to determine the distribution of the induced electric field (E-field) with high resolution, and with the ability to separately determine the E-field distribution within individual organs and tissues.

A difficulty with FDTD results is the presence of numerical artifacts at the interfaces between regions having disparate conductivity, and particularly at air/tissue interfaces (Reilly & Diamant, 2011, pp. 122-128). Such artifacts typically exaggerate the maximum E-field at the interfaces. A common method of dealing with these artifacts is to discard a small percentage of the largest values in each organ, such as the largest 1 percentile values, and retain the largest value (the 99th percentile rank) as representative of the "maximum" value (Kavet et al., 2012; Laasko & Hirata, 2012). Recent studies demonstrate that removing artifacts in FDTD solutions using this method, which is prescribed by the ICNIRP guidelines, can result in errors due to the discard of valid values or retention of invalid artifacts (De Santis and Chen, 2013; Laasko and Hirata, 2012).

[11] The FDTD model used in ICNIRP's 2010 guidelines is a considerable improvement over the simple circular loop model which was used to represent the body in the 1998 guidelines.

This method of artifact filtering may be satisfactory when determining averages or medians within specified volumes, as is done at high frequencies where the SAR metric may be appropriate. In such cases, large-value artifacts may have only a modest effect on the average. However, with electrostimulation phenomena, the potential for exciting a neuron more nearly depends on the maximum E-field value along a portion of its extended length, in a direction aligned with the neuron's axon. When evaluating the possibility of neuronal excitation, it is appropriate to average that peak field over a linear distance of about 5 mm (Reilly & Diamant, 2003; Reilly & Diamant, 2011, pp. 117 – 118), in which case included artifacts or discarded valid points may introduce a significant error.

The ICNIRP specification of volume averaging for determination of the electrostimulation potential (p. 825, col. 2) creates additional difficulties in assessing FDTD artifacts because, as an electrostimulation metric, a volume average may obscure the maximal linear average metric mentioned above.[12]

CNS limits below 20 Hz

BRs applicable to the CNS below 20 Hz have a flat plateau in the IEEE standard, but below 10 Hz rise in inverse proportion to frequency in the ICNIRP guidelines as is evident in magneto-phosphene experimental thresholds (Reilly, 1998). The motivation for the rising ICNIRP limit concerns accommodation due to the very low rate of rise of the waveform (Reilly & Diamant, 2011, pp. 78-80). This phenomenon is recognized in the IEEE standard, but a minimum plateau below 20 Hz is retained to account for an external magnetic field that might be suddenly switched on at a zero crossing, or a low frequency square wave (Reilly, 2005, p. 75, col. 1). In the first case, the induced *in situ* field would be equivalent to a long pulse; in the latter case, the fast rate of rise of the square wave would preclude accommodation.[13]

Environmental E-field limits

At frequencies where the IEEE electric field MPEs are proportional to $1/f$ (Table 5 specifies a range beginning at 368 Hz or 272 Hz for the general public and controlled environment, respectively, and ending at 3000 Hz), the limits are chosen such that a person of height 1.75 m who is insulated from ground and touching a grounded conductor would experience a current that is consistent with the limits for conducted contact current

[12] For limits based on CNS synaptic effects, volume averaging within a small region e.g., 1 mm^3, might be acceptable. Unlike excitation of a neuron along it axon, where the alignment of the field and axon trajectory is important, a post-synaptic cell sums the presynaptic inputs from as many as a thousand pre-synaptic cells, all accessing the post-synaptic cell at a myriad of directions (Koch & Segev, 1992). In this case, an average of the E-field over a small volume (e.g., 1 mm^3) may be more appropriate than a linear average (Jefferys, 1994).

[13] If a low frequency B-field is switched on at a zero crossing, the induced E- field (which is proportional to dB/dt) would be initiated at a peak, and would appear equivalent to a long monophasic electrostimulation pulse, i.e., a sudden rise to a peak, followed by a very gradual and lengthy fall.

with a fingertip contact, namely, 0.5 mA for the general public, and 1.5 mA for persons in controlled environments.[14]

A cap of 5 kV/m (general public) and 20 kV/m (controlled environment) is in place below the frequencies cited above to protect against painful spark discharges (See C95.6, Sect. 6.6 in reference to this paragraph). In addition, the IEEE standard allows an exposure of 10 kV/m (intermediate of limits for the general public and individuals in controlled environments) for power line rights-of-way (ROWs), with the understanding that public access is often allowed for public benefit. Moreover, IEEE C95.6 provides statistics concerning the possible impact of contact current and spark discharges that might ensue from this exception (C95.6, Sect. 6.6).

A similar calculation with the ICNIRP electric field limits result in contact current values of 69 μA for the general public, and 138 μA for occupational exposures in the frequency range 25 or 50 Hz to 3 kHz. These values are inconsistent with ICNIRP's contact currents limits, which are 0.5 and 1.5 mA for the general public and occupational groups, respectively. No justification is given in the ICNIRP guidelines for these E-field limits. Like IEEE, ICNIRP also caps exposure at 5 and 10 kV/m (general public and occupational exposures), but does not specify a power line ROW exception for the general public.

SUMMARY AND CONCLUSIONS

Human exposure limits to electromagnetic fields in the frequency range 1 Hz – 100 kHz have been developed by IEEE ICES and ICNIRP. This document presents the case for adoption of the IEEE limits for reasons summarized below. The following is a summary of the points covered in detail under the preceding sections of this document.

(1) **Objectives.** The stated objective of the IEEE standard is avoidance of adverse biological effects, which are defined to include aversive or painful reactions. ICNIRP also states the goal is avoidance of adverse reactions, but the physiological and behavioral meaning of "adverse" is not given and therefore it is unclear whether the specified limiting values are consistent with this goal.

(**2)** **Data trail.** The IEEE standards set a clear path from experimental thresholds and theoretical principles to the adopted limits. The ICNIRP guidelines do not show a clear connection between laboratory or theoretical studies and the adopted limits.

(3) **Safety/reduction factors**. The rationale behind the reduction factors are made clear in the IEEE standards, and separate components of those factors (probability and safety factors) are identified. ICNIRP does not explain the rationale behind its reduction factors.

(4) **Probability models and treatment**. The probabilities associated with reaction thresholds, including the limit values, are made clear in the IEEE standards. ICNIRP

[14] This result and the corresponding calculation for ICNIRP can be verified for a standing person 1.75 m tall, within a vertically polarized field using Eq. (10) of IEEE C95.6-2002 or Eq. 9.9 on p. 344 of Reilly, 1998, and the limit functions in Tables 5 and 6 in this paper.

does not acknowledge variability among subjects, nor does it define the statistical probabilities associated with its cited experimental thresholds and derived limit values.

(5) **Exposure of the limbs**. The IEEE standards provide separate limits for exposure of the limbs. ICNIRP does not.

(**6)** **Definition of exposed populations.** Two categories of exposed populations are identified in the IEEE standards: *General Public*, and *Persons in Controlled Environments*. The Occupational Exposure group defined in the ICNIRP guidelines could include individuals considered members of the general public in the IEEE standards.

(**7)** **Induction Models**. An ellipsoidal uniform conductivity (EUC) model is used in the IEEE standards to derive MPE values from the BRs. That model provides reasonably accurate values of the induced E-field within the body, and is free of artifacts. ICNIRP uses an FDTD model that can produce large artifacts and attempts to discard these artifacts using a criterion that could discard valid data or accept invalid artifacts.

(8) **CNS limits below 20 Hz**. The IEEE standard has frequency-independent CNS limits below 20 Hz in recognition of certain extremely-low-frequency waveforms for which stimulatory effects are unchanged as frequency declines below 20 Hz. However, ICNIRP allows for accommodation and therefore adopts limits that increase as frequency decreases below 10 Hz. Consequently, ICNIRP limits are significantly higher than IEEE limits below 5 Hz.

(9) **Environmental E-field limits – consistency**. MPEs for electric field exposure in the IEEE standards are consistent with contact current limits elsewhere in the standards. The ICNIRP E-field limits are inconsistent with its contact current limits. No justification is given by ICNIRP for its E-field limits.

(10) **Environmental E-field limits in power line ROWs.** Relaxed limits for the general public within power line ROWs are specified in the IEEE standards. ICNIRP makes no such exception.

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Table 1.IEEE Basic Restrictions, f = 1 Hz – 100 kHz (from IEEE-2002; 2005)

Exposed tissue	Freq. Range (Hz)	Basic Restriction, E_{BR} (V/m) Gen. Public	Contr. Env.
Brain [(a)]	1 – 20	5.8×10^{-3}	1.77×10^{-2}
	20 – 1k	$2.9 \times 10^{-4} f$	$8.85 \times 10^{-4} f$
Hands, wrists, feet, ankles	1 – 3.35k	2.10	2.10
	3.35k – 100k	$6.27 \times 10^{-4} f$	$6.27 \times 10^{-4} f$
Other tissue [(b)]	1 – 3.35k	0.701	2.10
	3.35k – 100k	$2.09 \times 10^{-4} f$	$6.27 \times 10^{-4} f$

Notes:
(a) BRs for brain are based on synaptic activity alteration. The upper limit of such interaction is not known. An upper limit of 1 kHz has been assumed.
(b) IEEE BRs for the heart are not shown here for brevity. "Other tissue" is all tissue other than brain; heart; hands, wrist, feet, & ankles.
(c) Data expressed as *RMS* values.
(d) In formulas, f is expressed in Hz.

Table 2. ICNIRP Basic Restrictions, f = 1 Hz – 100 kHz (from ICNIRP 2010)

Exposed tissue	General Public		Occupational Environment	
	Freq. Range (Hz)	E_{BR} (V/m)	Freq. Range (Hz)	E_{BR} (V/m)
Brain	1 - 10	$0.1/f$	1 - 10	$0.5/f$
	10 - 25	0.01	10 - 25	0.05
	25 – 1k	$4 \times 10^{-4} f$	25 – 400	$2 \times 10^{-3} f$
	1k – 3k	0.4	400 – 3k	0.8
	3k – 100k	$1.35 \times 10^{-4} f$	3k – 100k	$2.7 \times 10^{-4} f$
Other tissue[(a)]	1 – 3k	0.4	1 – 3k	0.8
	3k – 100k	$1.35 \times 10^{-4} f$	3k – 100k	$2.7 \times 10^{-4} f$

Notes:
(a) "Other tissue" includes everything other than brain. No special provisions made for limbs.
(b) Data expressed as *RMS* values.
(c) In formulas, f is expressed in Hz.

Table 3. IEEE Maximum permissible exposure (MPE) values for magnetic field exposure, f = 1 Hz – 100 kHz (from IEEE 2002; 2005).

Exposed body part	Freq. Range (Hz)	*RMS* MPE, B_{MPE} (mT)	
		Gen. Public	Contr. Env.
Head & torso	1 – 20	$18.1/f$	$54.3/f$
	20-759	0.904	2.71
	759-3.35k	$687/f$	$2060/f$
	3.35k – 100k	0.205	0.615
Limbs	1 – 10.7	353	353
	10.7 – 3.35k	$3790/f$	$3790/f$
	3.35k – 100k	1.13	1.13

Notes:
(a) In formulas, f is expressed in Hz.

Table 4. ICNIRP Reference Levels (RLs) for exposure to time-varying magnetic fields, f = 1 Hz – 100 kHz. No distinction is made for exposed body part.

General Public		Occupational Exposure	
Freq. Range (Hz)	Mag. flux density (mT)	Freq. Range (Hz)	Mag. flux density (mT)
1 - 8	$40/f^2$	1 - 8	$200/f^2$ (b)
8 - 25	$5/f$	8 - 25	$25/f$
25 – 400	0.2	25 - 300	1.0
400 – 3k	$80/f$	300 – 3k	$300/f$
3k – 100k	0.027	3k – 100k	0.10

Notes
(a) In formulas, f is expressed in Hz.
(b) Units of magnetic flux density in this table are in mT, rather than T as in ICNIRP document.

Table 5. IEEE Environmental electric field limits (MPEs as *RMS* values); whole body exposure; 1 Hz – 100 kHz

General Public		Controlled Environment.	
Freq. Range (Hz)	E_{MPE} (kV/m)	Freq. Range (Hz)	E_{MPE} (kV/m)
1 – 368	5	1 – 272	20
368 – 3k	$1.84 \times 10^3/f$	272 – 3k	$5.44 \times 10^3/f$
3k – 100k	0.614	3k – 100k	1.813

(a) In formulas, *f* is expressed in Hz.
(b) Within power line ROWs, the MPE for the general public is 10 kV/m under normal load conditions.
(c) The limit 20 kV/m may be exceeded in the controlled environment when a worker is not within reach of a conducting object.

Table 6. ICNIRP Environmental electric field limits, whole body exposure, 1 Hz – 100 kHz

General Public		Occupational Exposure	
Freq. Range (Hz)	E_{MPE} (kV/m)	Freq. Range (Hz)	E_{MPE} (kV/m)
1 - 50	5	1 - 25	20
50 – 3k	$2.5 \times 10^2/f$	25 – 3k	$5 \times 10^2/f$
3k – 100k	8.3×10^{-2}	3k – 100k	0.17

Notes
(a) In formulas, *f* is expressed in Hz, and *E* is in kV/m.

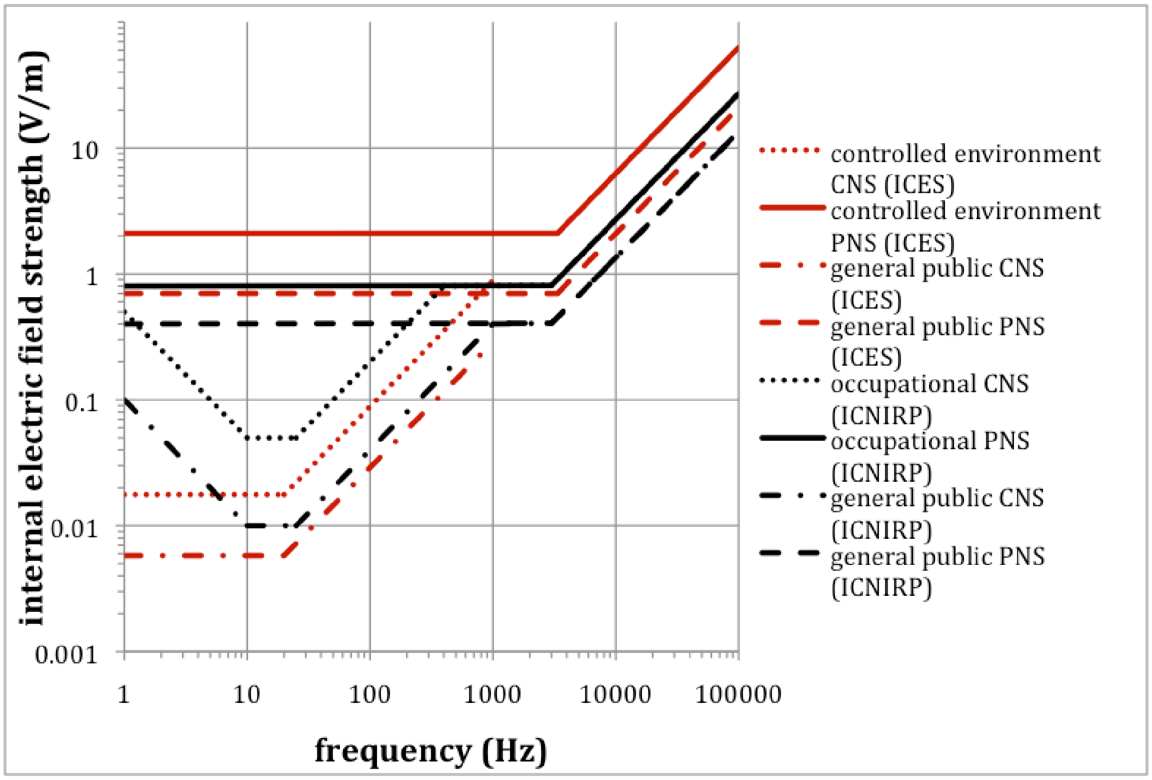

Figure 1. Basic Restrictions of IEEE C95.6-2002 (red) and ICNIRP-2010 (black) in the frequency range 1 Hz – 100 kHz. In the legend, "PNS" (upper 4 curves) refers to the peripheral nervous system; "CNS" (lower 4 curves) refers to the central nervous system—in particular, the brain).

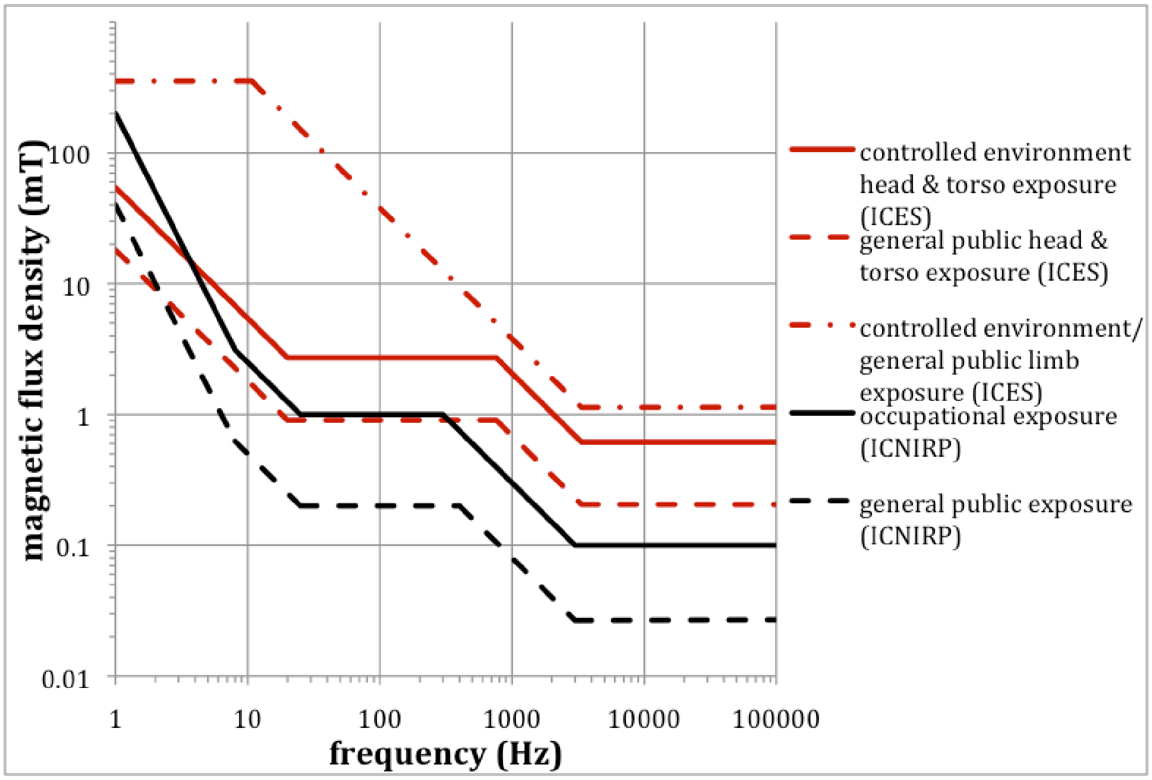

Figure 2. Maximum Permissible Exposure (MPE) values of the IEEE standard (red) and Reference Levels (RLs) of ICNIRP (black).