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IEEE Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Fields, 0–3 kHz

IEEE Standards Coordinating Committee 28

IEEE International Committee on
Electromagnetic Safety on Non-Ionizing Radiation



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IEEE Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Fields, 0–3 kHz

Sponsor

IEEE International Committee on Electromagnetic Safety
(Standards Coordinating Committee 28) on Non-Ionizing Radiation

Approved 12 September 2002
IEEE-SA Standards Board

Abstract: Recommendations are given to prevent harmful effects in human beings exposed to electromagnetic fields in the frequency range of 0–3 kHZ. The recommendations are intended to apply to exposures of the general public, as well as to individuals in controlled environments. They are not intended to apply to the purposeful exposure of patients by or under the direction of practitioners of the healing arts and may not be protective with respect to the use of medical devices or implants. A rationale that describes how the recommendations were arrived at, and the factors taken into account in formulating them, is included.
Keywords: contact currents, electric fields, electrical excitation, electromagnetic fields, electrostimulation, exposure limits, magnetic fields, non-ionizing radiation protection, safety levels

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Introduction

(This introduction is not part of IEEE Std C95.6-2002, IEEE Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Fields, 0–3 kHz.)

In 1960, the American Standards Association approved the initiation of the Radiation Hazards Standards project under the co-sponsorship of the Department of the Navy and the Institute of Electrical and Electronics Engineers.

Prior to 1988, C95 standards were developed by accredited standards committee C95 and submitted to the American National Standards Institute (ANSI) for approval and issuance as ANSI C95 standards. Between 1988 and 1990, the committee was converted to Standards Coordinating Committee 28 under sponsorship of the IEEE Standards Board, and in 2001, became also known as the International Committee on Electromagnetic Safety (ICES). In accordance with policies of the IEEE, C95 standards will be issued and developed as IEEE standards, as well as being submitted to ANSI for recognition.

The present scope of ICES is:

"Development of standards for the safe use of electromagnetic energy in the range of 0 Hz–300 GHz relative to the potential hazards due to exposure of such energy to man, volatile materials, and explosive devices. The committee will coordinate with other committees whose scopes are contiguous with ICES."

ICES is responsible for this standard. There are five subcommittees concerned with:

I Techniques, Procedures, Instrumentation, and Computation,

II Terminology, Units of Measurements, and Hazard Communication,

III Safety Levels with Respect to Human Exposure, 0–3 kHz,

IV Safety Levels with Respect to Human Exposure, 3 kHz–300 GHz,

V Safety Levels with Respect to Electro-Explosive Devices.

Two standards, two guides, and three recommended practices have been issued. Current versions are:

IEEE Std C95.1™-1999 Edition, IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz–300 GHz (Replaces IEEE Std C95.1-1991).

IEEE Std C95.2™-1999, IEEE Standard for Radio Frequency Energy and Current Flow Symbols (Replaces ANSI C95.2).

IEEE Std C95.3™-1991 (Reaff 1997), IEEE Recommended Practice for the Measurement of Potentially Hazardous Electromagnetic Fields—RF and Microwave (Replaces ANSI C95.3-1973 and ANSI C95.1-1981).

ANSI C95.5-1981, American National Standard Recommended Practice for the Measurement of Hazardous Electromagnetic Fields—RF and Microwave.

IEEE Std 1460™-1996, IEEE Guide for the Measurement of Quasi-Static Magnetic and Electric Fields.

ANSI C95.4-1978, American National Standard Safety Guide for the Prevention of Radio-Frequency Radiation Hazards in the Use of Electric Blasting Caps.

This standard was developed by an ICES Subcommittee 3 (SC 3) formed in 1991 to address the frequency range from 0–3 kHz (SC 3). In the early years, the subcommittee discussed the science relating to both long-

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term and short-term exposures and concluded that the effects of long-term (chronic) exposure were not convincingly established as were effects of short-term exposures.

Disclaimer

This IEEE standard was developed through the collaborative effort of an international group of volunteers with expertise in many disciplines ranging from medicine to engineering. While this standard represents a consensus among this volunteer group, it is not the only view on the safety issues addressed herein. As with any guidance, use of this standard, does not provide proof of or guarantee of absolute safety. Use and compliance with this IEEE standard is wholly voluntary.

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Grateful appreciation is expressed to J. Patrick Reilly for his major contributions to this standard through technical development, his chairmanship of the Working Group responsible for its development, his drafting of this standard, and his gracious permission to adapt the material in this standard from his own numerous publications on this subject.

The Committee also recognizes the contributions to this standard by the previous Subcommittee co-chairs, John A. Bergeron and William E. Feero.

In memoriam, we wish to recognize Matthew Mingoia, who served as Secretary of Subcommittee 3 from its formation in 1991 until his death in 2000, for his total dedication and support of the activities of the Subcommittee and his contributions to the development of this standard.

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IEEE Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Fields, 0–3 kHz

1. Overview

This standard is divided into six clauses. Clause 1 defines the scope and purpose of the standard. Clause 2 lists references to other standards that are useful in applying this standard. Clause 3 provides definitions that are either not found in other standards or have been modified for use with this standard. Clause 4 defines the protected population and the mechanisms of interaction. Clause 5 defines the exposure limits. Clause 6 details the rationale used in developing this standard.

1.1 Scope

This standard defines exposure levels to protect against adverse effects in humans from exposure to electric and magnetic fields at frequencies from 0–3 kHz. This standard was developed with respect to *established* mechanisms of biological effects in humans from electric and magnetic field exposures. It does not apply to exposures encountered during medical procedures. The defined exposure limits do not necessarily protect against interference of medical devices or problems involving metallic implants (see 6.12).

Established human mechanisms fall within the category of short-term effects. Such effects are understood in terms of recognized interaction mechanisms. Exposure limits defined in this standard are not based on the potential effects of long-term exposure because:

a) There is not sufficient, reliable evidence to conclude that long-term exposures to electric and magnetic fields at levels found in communities or occupational environments are adverse to human health or cause a disease, including cancer.
b) There is no confirmed mechanism that would provide a firm basis to predict adverse effects from low-level, long-term exposure.

The Subcommittee is aware of reported epidemiological associations between long-term exposure to magnetic fields and disease, including childhood leukemia in residential environments and chronic lymphocytic leukemia in occupational environments. The interpretation of these associations is unclear, especially since exposure to magnetic fields does not appear to initiate or advance the development of leukemia or other forms of cancers and other diseases in animals exposed over much of their lifetime. This is

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consistent with the findings of interdisciplinary panels of scientists that have evaluated the literature on long-term exposures for scientific and governmental organizations. The most recent of these major reviews include the Advisory Group on Non-Ionizing Radiation of the UK National Radiological Protection Board (AGNIR [B3][1]), the Health Council of the Netherlands (Netherlands [B63]), the U.S. National Institute of Environmental Health Sciences (NIEHS [B64]; Olden [B68]), the Institution of Electrical Engineers (IEE [B45]), the International Agency for Research on Cancer (IARC [B42]), the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [B43], and the U. S. National Research Council (NRC [B65]).

Because none of the above reviews concluded that any hazard from long-term exposure has been confirmed, this standard does not propose limits on exposures that are lower than those necessary to protect against adverse short-term effects. The Subcommittee will continue to evaluate new research and will revise this standard should the resolution of present uncertainties in the research literature identify a need to limit long-term exposures to values lower than the limits of this standard. The Subcommittee will also continue to evaluate new research on short-term effects and modeling. As stated below, this standard makes reasonable assumptions based upon available data. As new data becomes available, the committee will revisit these assumptions for future revisions.

1.2 Purpose

The IEEE has previously defined safety standards for human exposure to electromagnetic fields in the frequency regime from 3 kHz–300 GHz (IEEE [B46]). The purpose of this standard is to define exposure standards for the frequency regime 0–3 kHz. For pulsed or nonsinusoidal fields, it may be necessary to evaluate an acceptance criterion at frequencies outside this frequency regime as explained in 5.2.4.2.

2. References

This standard shall be used in conjunction with the following publications:[2]

Accredited Standards Committee C2-1997, National Electrical Safety Code® (NESC®).[3]

IEEE Std 644™-1994, IEEE Standard Procedures for Measurement of Power Frequency Electric and Magnetic Fields from AC Power Lines.[4]

IEEE Std 1460™-1996, IEEE Guide for the Measurement of Quasi-Static Magnetic and Electric Fields.

3. Definitions, acronyms, and symbols

3.1 Definitions

For the purposes of this standard, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms,* Seventh Edition [B47], shall be referenced for terms not defined in this clause.

3.1.1 action potential: A response of a nerve cell to a stimulus involving a propagating rapid depolarization of the potential across the cell membrane.

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[1]The numbers in brackets correspond to those of the bibliography in Annex A.

[2]The IEEE standards referred to in Clause 2 are trademarks of the Institute of Electrical and Electronics Engineers, Inc.

[3]The NESC is available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).

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3.1.2 adverse effect: An effect detrimental to the health of an individual due to exposure to an electric or magnetic field, or a contact current.

3.1.3 adverse reaction factor (F_a): A multiplier used to derive maximum permissible exposure (MPE) levels, which converts from a threshold reaction to an adverse one.

3.1.4 averaging distance: The distance over which the *in situ* electric field is averaged when determining compliance with basic restrictions.

3.1.5 averaging time: The appropriate time period over which exposure is averaged for purposes of determining compliance with a maximum permissible exposure (MPE) or Reference Level.

3.1.6 axial cross section: A cross section of the body taken in a plane perpendicular to its long axis.

3.1.7 axial exposure: Exposure by a magnetic field perpendicular to the axial cross section.

3.1.8 basic restrictions: Limitations on the *in situ* electrical forces that avoid adverse effects, and with an acceptable safety factor.

3.1.9 biphasic: A waveform that has a reversal of polarity.

3.1.10 cardiac excitation: The electrical stimulation of a cardiac contraction.

3.1.11 central nervous system (CNS): The portion of the vertebrate nervous system consisting of the brain and spinal cord, but not including the peripheral nerves.

3.1.12 cerebral cortex: The convoluted thin layer of brain cells (gray matter) forming the outer surface of each cerebral hemisphere.

3.1.13 conductivity: A property of materials that determines the magnitude of the electric current density when an electric field is impressed on the material, expressed in units of siemens per meter (S/m); the inverse of resistivity.

3.1.14 contact current: Current passed into a biological medium via a contacting electrode or other source of current.

3.1.15 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 effects.

3.1.16 corona (air): A luminous discharge due to ionization of the air surrounding a conductor caused by a voltage gradient exceeding a certain critical value.

3.1.17 coronal cross section: A cross section taken through the long axis of the body in a plane parallel to its front view.

3.1.18 coronal exposure: Exposure by a magnetic field perpendicular to the coronal cross section.

3.1.19 depolarization (cellular): The reduction of the resting potential across a cellular membrane.

3.1.20 direct electrostimulation: Stimulation via the electric field within the biological medium induced by an external electric or magnetic field without direct contact with other conductors or spark discharges.

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3.1.21 electric field strength (*E*): Force exerted by an electric field on an electric point charge, divided by the electric charge. Electric field strength is expressed in newtons per coulomb or volts per meter (N/C = V/m).

3.1.22 electrostimulation: Induction 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.

3.1.23 environmental field: An electric or magnetic field external to the body and measured in the absence of the body.

3.1.24 established mechanism: A bioelectric mechanism having the following characteristics: (a) can be used to predict a biological effect in humans; (b) an explicit model can be made using equations or parametric relationships; (c) has been verified in humans, or animal data can be confidently extrapolated to humans; (d) is supported by strong evidence; and (e) is widely accepted among experts in the scientific community.

3.1.25 extra systole: An induced cardiac contraction, usually a premature contraction that interrupts the normal sinus rhythm; a forced heartbeat.

3.1.26 general public: All individuals who may experience exposure, except those in controlled environments.

3.1.27 grasping contact: An electrical connection with a large energized conductor made by firmly holding the conductor in the hand. In this standard, a contact area of 15 cm^2 is assumed for such contact.

3.1.28 Hall-effect voltage: The voltage developed between two points within a conductive medium due to the redistribution of moving charges in a magnetic field.

3.1.29 indirect electrostimulation: Stimulation through contact with a conducting object under the influence of an electric or magnetic field, including spark discharges.

3.1.30 induction: An electric or magnetic field in a conducting medium caused by the action of a time-varying external (environmental) electric or magnetic field.

3.1.31 *in situ*: Within biological tissue.

3.1.32 let-go current: The threshold current level at which involuntary muscular contraction prevents release of a grip on an energized conductor.

3.1.33 lognormal distribution: A statistical distribution in which the logarithm of the statistical variate is normally distributed.

3.1.34 Lorentz force: The force on a moving charge within a magnetic field.

3.1.35 magnetic field strength (*H*): The magnitude of the magnetic field vector; expressed in units of amperes per meter (A/m).

3.1.36 magnetic flux density (*B*): A vector quantity that determines the force on a moving charge or charges (electric current). Magnetic flux density is expressed in teslas (T). One gauss (deprecated unit) equals 10^{-4} T.

3.1.37 magnetohydrodynamic effect: A force or potential imparted on a fluid volume arising from its motion in the presence of a magnetic field.

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3.1.38 maximum permissible exposure (MPE): The rms and peak electric and magnetic fields and contact currents to which a person may be exposed without an adverse effect and with acceptable safety factors. The MPE for magnetic field exposure in this standard may be exceeded if it can be demonstrated that the basic restrictions are not exceeded.

3.1.39 mean: The arithmetic average of a series of measurements or other data.

3.1.40 median: The value within a statistical distribution at which 50% of data are above and below.

3.1.41 median threshold: The threshold value within a statistical distribution at which 50% of subjects have greater thresholds and 50% have lesser thresholds.

3.1.42 monophasic: A waveform not reversing in polarity.

3.1.43 motor neuron: (a) A central neuron that initiates excitation of a peripheral nerve; (b) a peripheral nerve that innervates muscle. Definition (b) is generally used in this standard.

3.1.44 myelinated nerve: A nerve fiber containing insulating myelin sheaths that are interrupted by uninsulated segments called *nodes of Ranvier.*

3.1.45 nerve: A bundle of axons.

3.1.46 nerve fiber: A single nerve axon.

3.1.47 neuron: A single cellular unit usually consisting of an axon, cell body, and dendritic tree.

3.1.48 nonuniform field: A field that is not constant in amplitude, direction, and relative phase over the dimensions of the body or body part under consideration. In the case of electric fields, the definition applies to an environmental field undisturbed by the presence of the body.

3.1.49 normal load conditions: The maximum operating voltage and current of an electric power transmission line under conditions that exclude outages, or other emergency operating conditions.

3.1.50 open-circuit voltage: The potential difference between two conducting objects without a current load being applied to the objects.

3.1.51 peripheral nerve: Nerve found outside the central nervous system and leading to and from the central nervous system.

3.1.52 phase duration (t_p): The time between zero crossings of a waveform having zero mean. For a sine-wave 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.

3.1.53 phosphene: Visual sensation caused by nonphotic stimuli. Electro-phosphenes are induced by electric currents; magneto-phosphenes are induced magnetically.

3.1.54 polarization (cellular): The electric potential formed across a cell membrane.

3.1.55 postsynaptic cell: The cell receiving excitation in a synaptic junction between two nerve cells.

3.1.56 presynaptic cell: The cell that provides excitation at a synapse, usually by release of a neurotransmitter.

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3.1.57 probability factor (F_p): A multiplier used in the derivation of maximum permissible exposure (MPE) or reference levels, which converts a median threshold to a low probability one (≤ 1%).

3.1.58 proposed mechanism: A bioelectric mechanism lacking the characteristics of an established mechanism. **(See also:** *established mechanism.*)

3.1.59 relative phase: The phase angle of a sinusoidal waveform relative to the phase angle of another waveform measured at a different point within the conductive medium or with respect to a stated reference waveform.

3.1.60 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.

3.1.61 root-mean-square (rms): A mathematical operation on a series of measurements (or a temporal sequence of data) in which the square root of the arithmetic mean of the squares of the measurements or data is taken.

3.1.62 safety factor (F_s): A multiplier (≤ 1) used to derive maximum permissible exposure (MPE) levels, which provides for the protection of exceptionally sensitive individuals, uncertainties concerning threshold effects due to pathological conditions or drug treatment, uncertainties in reaction thresholds, and uncertainties in induction models.

3.1.63 sagittal cross section: A cross section along the long axis of the body, parallel to its side view.

3.1.64 sagittal exposure: Exposure by a magnetic field perpendicular to the sagittal cross section.

3.1.65 short-term response: A biological response to an electric or magnetic stimulus manifested within a few seconds after the exposure begins.

3.1.66 spark discharge: The transfer of current through an air gap requiring a voltage high enough to ionize the air, as opposed to direct contact with a source.

3.1.67 specific absorption rate (SAR): The time derivative of the incremental energy absorbed by (dissipated in) an incremental mass contained in a volume element of given density. SAR is expressed in watts per kilogram (W/kg).

3.1.68 strength-duration curve: The functional relationship between the threshold of excitation and the duration of an excitatory stimulus.

3.1.69 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.

3.1.70 strength-frequency curve: The functional relationship between the threshold of excitation and the frequency of an excitatory stimulus.

3.1.71 synapse: The site of functional apposition between two neurons at which an electrical signal from one neuron is transmitted to another by either electrical or chemical means. In the typical synapse, the impulse is transmitted by a chemical substance called a *neurotransmitter.*

3.1.72 systole: Contraction of the heart.

3.1.73 threshold: The level of a stimulus marking the boundary between a response and a nonresponse.

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3.1.74 touch contact: A contact of small area made between the human body and an energized conductor. In this standard, a contact area of one cm^2 is the assumed touch contact area.

3.1.75 uniform field: A field that is constant in amplitude, direction, and relative phase over the dimensions of the body or body part under consideration. In the case of electric fields, the definition applies to an environmental field undisturbed by the presence of the body.

3.1.76 ventricular fibrillation: Arrhythmia of the ventricles of the heart characterized by rapid uncoordinated contractions.

3.1.77 visual evoked potential (VEP): An endogenous potential ensuing in the brain and measured on the scalp in response to a visual stimulus.

3.1.78 voxel: A three-dimensional computational element.

3.1.79 waveform: The variation of an electrical amplitude with time. Unless otherwise stated, in this standard the term *waveform* refers to values (or measurements) at sites within the biological medium.

3.2 Acronyms and abbreviations

B-field Magnetic flux density

CNS Central nervous system

E-field Electric field strength

ECT Electroconvulsive therapy

EMC Electromagnetic compatibility

IARC International Agency for Research on Cancer

ICNIRP International Commission on Non-Ionizing Radiation Protection

IEE Institute of Electrical Engineers (United Kingdom)

MPE Maximum permissible exposure

MRI Magnetic resonance imaging

NIEHS National Institute of Environmental Health Sciences (USA)

NRC National Research Council (USA)

rms Root-mean-square

SAR Specific absorption rate

S-D Strength-duration (time constant, curve, etc.)

VEP Visual evoked potential

VF Ventricular fibrillation

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3.3 Symbols

a, b Semi-major and semi-minor axes of elliptical representation of exposed body part.

A_i The magnitude of the *i*th Fourier component of a waveform.

B Magnetic flux density, expressed in tesla (T). Tesla and gauss (G) units are related by 1 G = 10^{-4} T.

B_o The minimum flux density in a strength-duration or strength-frequency relationship (T).

$\dot{B}$ Time rate of change of magnetic flux density, *dB/dt*, expressed as teslas-per-second (T/s).

$\dot{B}_p$ Peak allowable limit on the time derivative of flux density.

d_a Averaging distance used to determine compliance with an *in situ* electric field basic restriction.

d_e Spatial extent of an *in situ* electric field.

E Electric field strength, expressed in volts-per-meter (V/m).

E_o The minimum (rheobase) electric field strength in a strength-duration or strength-frequency relationship (V/m).

E_{ot} Rheobase threshold electric field strength.

E_{ob} Rheobase basic restriction.

E_i *In situ* electric field (V/m).

f Frequency, expressed in hertz (Hz).

f_e Upper transition frequency in a strength-frequency relation (Hz).

f_i Frequency of the *i*th Fourier component of a waveform.

F_a Adverse reaction factor.

F_p Probability factor.

F_s Safety factor.

h Height of standing person, expressed in meters (m).

H Magnetic field intensity, expressed in amperes-per-meter (A/m). Related to flux density by $B = \mu H$.

I_c Contact current, expressed in amperes (A).

J Current density, expressed in amperes-per-square meter (A/m^2).

ME_i Maximum allowable exposure of either the *in situ* electric field, the environmental field, or the contact current at frequency f_i.

μ Magnetic permeability, expressed in henries-per-meter (H/m).

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μ_o Magnetic permeability in a vacuum or in air: $\mu_o = 4\pi \times 10^{-7}$ H/m.

σ Conductivity of medium, expressed in siemens-per-meter (S/m).

τ_e Transition duration in a strength-duration relationship, expressed in seconds (s).

τ_h Time constant of the leakage of charge applied to a human subject.

t_p Phase duration (s).

4. Protected population and mechanisms of interaction

4.1 Protected population

Protection is to be afforded to individuals in the general population and to groups in controlled environments. It is assumed that for the controlled environment, education and various mitigating measures can be taken to reduce the probability of adverse reactions of exposed individuals, although the exposure limits should protect against adverse effects for almost all people, with the possible exception of spark discharges within electric fields in the controlled environment. However, if adverse effects under some circumstances are anticipated, they can be mitigated with precautionary measures that are appropriate to the anticipated exposure situation. Examples of such measures include protective gloves or clothing, awareness programs designed to alert personnel to the possibility of effects, or specific work practices that lessen the frequency or intensity of exposure. For the general public accessibility is unconstrained and may include individuals uninformed of the potential for exposure or of possible adverse effects. Such exposure may occur in living quarters, areas open to the general public, workplaces where individuals do not anticipate exposure, or workplaces where workers are not aware of exposure conditions or prevention and mitigation procedures.

4.2 Mechanisms of biophysical reactions

An established human mechanism is one having the following characteristics:

a) It can be used to predict biological effects in humans; (b) an explicit model can be made using equations or parametric relationships.
b) It has been verified in the intact human, or animal data can be confidently extrapolated to humans.
c) It is supported by strong evidence.
d) It is widely accepted among experts in the scientific community.

Mechanisms not having these characteristics are classified as *proposed.* Progress in research on proposed mechanisms should be monitored and evaluated as to whether any can be included in the list of established mechanisms.

Established mechanisms have been identified based on these criteria (Reilly [B75], [B76], [B77]). One class of mechanisms relates to membrane polarization, i.e., the alteration of the cellular membrane's natural resting potential by the *in situ* electric field. Depolarization of the membranes of nerve and muscle can lead to their excitation *herein referred to as electrostimulation*; these effects are responsible for the minimum thresholds of reaction at frequencies from about 1 Hz to above 3 kHz (the limit of this standard). Magnetohydrodynamic effects, which apply to forces on moving charges in fluids, dominate biological reactions below 1 Hz. These mechanisms produce short-term effects, i.e., they result in reactions to electric and magnetic fields that are manifested within seconds, (usually a fraction of a second) after the exposure begins. Thermal effects are well-understood, but are not dominant at frequencies below 100 kHz, and therefore do not affect the exposure limits defined in this document.

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The fundamental force responsible for electrostimulation effects is the *in situ* electric field, rather than the internal current density (see 6.1). More accurate limits for electrostimulation effects can be derived as a function of the *in situ* electric field rather than internal current density as has been a common practice in the past (Bernhardt [B11]; ICNIRP [B43]; IEEE [B46]). The distribution within the body of *in situ* electric fields differs from the distribution of current density, and the calculation of the *in situ* electric field is less sensitive to assumptions of tissue conductivities compared to internal current density.

Mechanisms of interaction that are classified as *proposed* relate to long-term or chronic exposure effects (Olden [B68]; Reilly [B76]). These mechanisms are typically mentioned in connection with hypotheses concerning effects of chronic exposure to low-level electric and magnetic fields, including cancer, reproductive effects, nervous system effects, etc. While these mechanisms cannot be dismissed as being irrelevant, the body of knowledge concerning them is presently insufficient to establish a confirmed mechanism that would provide a firm basis for deriving human exposure limits.

4.3 Adverse biological effects

Maximum exposure limits are based on avoidance of the following short-term reactions:

a) Aversive or painful stimulation of sensory or motor neurons
b) Muscle excitation that may lead to injury while performing potentially hazardous activities
c) Excitation of neurons or direct alteration of synaptic activity within the brain
d) Cardiac excitation
e) Adverse effects associated with induced potentials or forces on rapidly moving charges within the body, such as in blood flow

5. Exposure limits

5.1 Basic restrictions

Basic restrictions refer to limitations on the *in situ* electrical forces that adequately avoid adverse effects. Such restrictions are derived with consideration of adverse electrical thresholds, their distribution among the population, and safety factors (see Clause 6).

Table 1 lists basic restrictions for particular areas of the body in terms of the electric field within the biological medium. Two parameters are listed in the table: the rheobase *in situ* field, E_o, and a frequency parameter, f_e. Limits are determined from Table 1 as shown in Equation (1a) and Equation (1b):

$$E_i = E_0 \quad \text{for } f \le f_e \tag{1a}$$

$$E_i = E_0 (f / f_e) \quad \text{for } f \ge f_e \tag{1b}$$

where E_i is the maximum permissible induced *in situ* electric field. The basic restrictions on the *in situ* electric field apply to an arithmetic average determined over a straight line segment of 0.5 cm length oriented in any direction within the tissue identified in Table 1.

In addition to the listed *in situ* electric field restrictions of Table 1, the *in situ* magnetic field below 10 Hz should be restricted to a peak value of 167 mT for the general public and 500 mT in the controlled environment. For frequencies above 10 Hz, a basic restriction on the *in situ* magnetic field is not specified in this standard.

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Table 1—Basic restrictions applying to various regions of the body[a, b]

Exposed tissue	f_e (Hz)	General public	Controlled environment
		E_0 - rms (V/m)	E_0 - rms (V/m)
Brain	20	5.89×10^{-3}	1.77×10^{-2}
Heart	167	0.943	0.943
Hands, wrists, feet and ankles	3350	2.10	2.10
Other tissue	3350	0.701	2.10

[a]Interpretation of table is as follows: $E_i = E_0$ for $f \le f_e$; $E_i = E_0\,(f / f_e)$ 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.

5.2 Maximum permissible exposure (MPE) values: Magnetic flux density

5.2.1 Exposure of the head and torso to sinusoidal fields

Table 2 lists maximum permissible magnetic field limits (flux density, *B*, and magnetic field strength, *H*) for exposure of the head and torso. The averaging time for an rms measure is 0.2 seconds for frequencies above 25 Hz. For lower frequencies, the averaging time is such that at least 5 cycles are included in the average, but with a maximum of 10 seconds.

Table 2—Magnetic maximum permissible exposure (MPE) levels: exposure of head and torso[a, b]

Frequency range (Hz)	General public		Controlled environment	
	B - rms (mT)	*H* - rms (A/m)	*B* - rms (mT)	*H* - rms (A/m)
< 0.153	118	9.39×10^4	353	2.81×10^5
0.153–20	$18.1/f$	$1.44 \times 10^4/f$	$54.3/f$	$4.32 \times 10^4/f$
20–759	0.904	719	2.71	2.16×10^3
759–3000	$687/f$	$5.47 \times 10^5/f$	$2060/f$	$1.64 \times 10^6/f$

[a]f is frequency in Hz.
[b]MPEs refer to spatial maximum.

Compliance with Table 2 ensures compliance with the basic restrictions of Table 1. However, lack of compliance with Table 2 does not necessarily imply lack of compliance with the basic restrictions, but rather that it may be necessary to evaluate whether the basic restrictions have been met. If the basic restrictions in Table 1 are not exceeded, then the MPE values in Table 2 can be exceeded. Consequently, it is sufficient to demonstrate compliance with either Table 1 or Table 2.

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For purposes of demonstrating compliance with this standard, Table 2 and Table 4 shall be considered separately, and not additively.

Entries in Table 1 and elsewhere in this standard are sometimes given to three significant digits. This degree of precision is provided so that the reader can follow the various derivations and relationships presented in this standard and does not imply that the numerical quantities are known to that precision.

5.2.2 Nonuniform exposure to sinusoidal magnetic fields

When the magnetic field is not constant in magnitude, direction, or relative phase over the head and torso, the maximum field over the head and torso shall be limited to the levels in Table 2. Alternatively, it shall be permitted to demonstrate adherence to the basic restrictions.

5.2.3 Exposure of the arms or legs

Maximum permissible exposure (MPE) levels for the arms or legs are listed in Table 3. Compliance with Table 3 ensures compliance with the basic limitations of Table 1. However, lack of compliance with Table 3 does not necessarily imply lack of compliance with the basic restrictions, but rather that it may be necessary to evaluate whether the basic restrictions are met.

Table 3—Magnetic flux density maximum permissible exposure levels: exposure of arms or legs[a]

Frequency range (Hz)	General public *B* - rms (mT)	Controlled environment *B* - rms (mT)
< 10.7	353	353
10.7–3000	3790/*f*	3790/*f*

[a]*f* is frequency in Hz.

5.2.4 Pulsed or nonsinusoidal fields

When the magnetic flux density waveform is nonsinusoidal, maximum permissible exposure shall conform to the *rms* limits of Table 1 or Table 2. In addition, maximum exposure limits shall conform to either 5.2.4.1 or 5.2.4.2. (Since both criteria are conservative, adherence to either is sufficient to demonstrate compliance with maximum permissible exposure limits or the basic restrictions.)

5.2.4.1 Restriction based on peak field

Demonstration of compliance with either of the following two subclauses is sufficient to demonstrate compliance with restrictions based on the peak field. Subclause 5.2.4.1.1 applies to the *in situ* induced electric field. Subclause 5.2.4.1.2 applies to the environmental field.

5.2.4.1.1 Peak *in situ* field

The peak *in situ* electric field shall be restricted to a value obtained by multiplying the rms limits of Table 1 by $\sqrt{2}$. To interpret this table for nonsinusoidal waveforms, frequency, *f*, is defined as $f = 1/(2t_p)$, where t_p is the phase duration of a peak excursion of the *in situ* electric field. Phase duration is defined as time between zero crossings of a waveform having zero mean. 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. Peak

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limits apply to instantaneous values measured through a bandwidth from zero to the highest frequency applicable to the waveform under consideration.

5.2.4.1.2 Peak environmental field

The peak environmental magnetic field, *B*, shall be limited according to the following procedure, where *B* is a time-varying flux density waveform whose compliance is under question.

a) Determine the time derivative of the environmental field, $dB/dt = \dot{B}$.
b) Identify the peak and phase duration of any excursion of $\dot{B}$. Phase duration shall be determined as in 5.2.4.1.1.
c) Determine the allowable peak limit on $\dot{B}$ from Table 2 as $\dot{B}_p = \sqrt{2}\, MPE_B(2\pi f)$, where $\dot{B}_p$ is the maximum permissible value of $\dot{B}$, MPE_B is the flux density consistent with Table 2 and Table 3, $f = 1/(2t_p)$, and t_p is the phase duration of $\dot{B}$.

5.2.4.2 Restriction based on Fourier components

For an exposure waveform consisting of multiple frequencies, a test for compliance of the exposure waveform shall satisfy the following criterion:

$$\sum_{0}^{5\text{MHz}} \frac{A_i}{ME_i} \leq 1 \qquad (2)$$

where

A_i is the magnitude of the *i*th Fourier component of the exposure waveform,
ME_i is the maximum permissible exposure or the basic *in situ* field restriction with a single sinusoidal waveform at a frequency f_i.

The summation is carried out from the lowest frequency of the exposure waveform, to a maximum frequency of 5 MHz. Note that A_i and ME_i must measure the same quantity, as well as be in the same units. For instance, if A_i is the magnitude of a flux density waveform, then ME_i must also be a measure of flux density. Alternatively, both A_i and ME_i could be measures of the time derivative of the field, the induced *in situ* electric field, or induced current density.

It may be necessary to evaluate Equation (2) at frequencies outside the limits of this standard. For purposes of such evaluation, the ME_i values applying to frequencies greater than 3 kHz shall be determined as follows.

a) *Basic restrictions* (Table 1). Rheobase values of the *in situ* electric field (E_{ob}) shall be assumed for frequencies from f_e to 5 MHz.
b) *Magnetic field MPEs* (Table 2 and Table 3). The MPE value of *B* or *H* shall be determined to a maximum frequency of 3350 Hz using the formulae listed in the last row of the table. From 3350 Hz–5 MHz, the MPE value shall equal that at 3350 Hz.
c) *Electric field MPEs* (Table 4). The MPE value applicable to 3000 Hz shall be assumed to a maximum frequency of 5 MHz.
d) *Induced and contact current MPEs* (Table 5). The MPE value listed at 3000 Hz shall be extrapolated to a maximum frequency of 5 MHz using the relationship: $MPE_i = MPE_{3000}\,(f/3000)$ where MPE_i is the limit at the appropriate frequency between 3 kHz and 5 MHz, MPE_{3000} is the limit at 3000 Hz, and *f* is the frequency in Hz.

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5.3 Maximum permissible exposure values: environmental electric fields

5.3.1 Constant whole-body exposure to sinusoidal electric fields

Table 4 lists maximum electric field limits in terms of the undisturbed (absent a person) environmental field, *E*. It is assumed that the undisturbed field is constant in magnitude, direction, and relative phase over a spatial extent that would fit the human body. The averaging time for an rms measure shall be 0.2 seconds for frequencies above 25 Hz. For lower frequencies, the averaging time is such that at least 5 cycles are included, with a maximum of 10 seconds. For a controlled environment in which an exposed individual is not within reach of a grounded object, it may be acceptable to exceed the limits listed in Table 4. This standard does not specify limits for situations involving contact with ungrounded objects.

For purposes of demonstrating compliance with this standard, Table 2 and Table 4 shall be considered separately, and not additively.

Table 4—Environmental electric field MPEs, whole body exposure

General public		Controlled environment	
Frequency range (Hz)	***E* - rms (V/m)**	**Frequency range (Hz)**	***E* - rms (V/m)**
1–368[c]	5000[a,d]	1–272[c]	20 000[b,e]
368–3000	$1.84 \times 10^6/f$	272–3000	$5.44 \times 10^6/f$
3000	614	3000	1813

[a]Within power line rights-of-way, the MPE for the general public is 10 kV/m under normal load conditions.
[b]Painful discharges are readily encountered at 20 kV/m and are possible at 5–10 kV/m without protective measures.
[c]Limits below 1 Hz are not less than those specified at 1 Hz.
[d]At 5 kV/m induced spark discharges will be painful to approximately 7% of adults (well-insulated individual touching ground).
[e]The limit of 20 000 V/m may be exceeded in the controlled environment when a worker is not within reach of a grounded conducting object. A specific limit is not provided in this standard.

5.3.2 Nonuniform or partial body exposure to sinusoidal electric fields

When the environmental electric field is not constant in magnitude, direction, and relative phase over the dimensions of the human body, the average environmental field shall be restricted to the levels in Table 4. For a controlled environment in which an exposed individual is not within reach of a grounded conducting object, it may be acceptable to exceed the limits listed in Table 4. This standard does not specify limits for such cases. In no case shall the basic limitations of Table 1 or the contact current limits of Table 5 be exceeded.

5.3.3 Pulsed or nonsinusoidal fields

When the waveform of the electric field is nonsinusoidal, such as with pulsed or mixed frequency waveforms, MPE limits shall conform to the rms limits of Table 4 and also to either of the criteria stated in 5.2.4.1 and 5.2.4.2. For this application, the environmental magnetic field is replaced by the undisturbed electric field, A_i is understood to represent the magnitude of the *i*th Fourier component of the environmental electric field waveform, and ME_i is the maximum permissible electric field magnitude at frequency f_i.

With respect to electric field exposure, 5.2.4.1.2 and 5.2.4.2 shall apply to frequencies from 368–3000 Hz for the general public, and from 272–3000 Hz in controlled environments. Below those frequencies and above

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1 Hz, peak electric fields shall not exceed 7100 and 28 000 V/m for the general public and controlled environments, respectively, and 14 100 V/m for the general public within powerline rights-of-way.

5.4 Contact and induced current maximum permissible exposure limits

5.4.1 Sinusoidal current

Contact current shall be limited as indicated in Table 5, subject to the following conditions:

a) Table 5 limits for freestanding individuals without contact with metallic objects shall not exceed the values listed in the rows labeled “Both feet” and “Each foot.”

b) Contact limits in Table 5 assume a freestanding individual who is insulated from ground while touching a conductive path to ground. The criteria do not necessarily protect against aversive sensations from spark discharges just prior to and just after the moment of direct contact with the ground path.

c) The averaging time for rms current measurements shall be 0.2 seconds for frequencies above 25 Hz. For lower frequencies, the averaging time shall include at least 5 cycles, with a maximum of ten seconds. The limits for peak exposure refer to instantaneous values measured through a bandwidth from zero to the highest frequency of interest.

d) In controlled environments, limits for grasp contacts apply where personnel are trained to make grasping contact and to avoid touch contacts with conductive objects that present the possibility of painful contact current. A grasp contact area is assumed to be 15 cm^2. The use of protective gloves, the prohibition of metallic objects, or training of personnel may be sufficient to assure compliance with contact current MPE in controlled environments. For the general public, it is assumed that access, methods of contact, and protective measures are unconstrained.

e) For the general public, a touch contact is assumed to have a contact area of 1 cm^2.

Table 5— Induced and contact current MPEs (mA-rms) for continuous sinusoidal waveforms, 0–3 kHz[a, b]

Condition	General public (mA, rms)	Controlled environment (mA, rms)
Both feet	2.70	6.0
Each foot	1.35	3.0
Contact, grasp	—	3.0
Contact, touch	0.50	1.5

[a]Grasping contact limit pertains to controlled environments where personnel are trained to effect grasping contact and to avoid touch contacts with conductive objects that present the possibility of painful contact.

[b]Limits apply to current flowing between body and grounded object that may be contacted by the person.

5.4.2 Nonsinusoidal (pulsed or mixed frequency) current

When the current waveform is nonsinusoidal, such as with pulsed or mixed frequency waveforms, MPE limits shall conform to the rms limits of Table 5 and also to either of the criteria stated in 5.2.4.1 and 5.2.4.2. For this application, the environmental field is replaced by the applied current, A_i is understood to represent the magnitude of the ith Fourier component of the current waveform, and ME_i is the maximum permissible current magnitude at frequency f_i.

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6. Rationale

6.1 Excitation thresholds: strength-duration and strength-frequency laws

The parameter that drives the process of electrostimulation is the depolarization of the excitable cellular membrane (nerve or muscle) (Reilly [B75]). This modification of the cellular resting potential by an applied electrical stimulus is determined by the electric field in the medium surrounding the excitable tissue (the component of the field parallel to the long axis of the cell), or equivalently, the change in electric potential exterior to the cell. Knowledge of either the electric field or its spatial gradient is required to assess electrostimulation. Of course, the electric field can be derived from the current density by taking the ratio J/σ, where σ is the conductivity of the medium. But basing a standard on current density rather than the *in situ* electric field introduces an additional parameter, and that introduces an uncertainty beyond that which already existed in deriving the electric field itself. Thus, the *in situ* electric field is used as the fundamental metric in this standard.

An *in situ* electric field strength-duration curve, which defines thresholds for monophasic stimulus waveforms, is defined by two parameters: the minimum *(rheobase)* excitation threshold, E_o, and the strength-duration time constant, τ_e. Values of E_o and τ_e differ considerably for nerve excitation, muscle excitation, and synaptic activity alteration. Table 6 lists median threshold assumptions on E_o and τ_e underlying these standards. Peak electric field thresholds are determined from Table 6 and Equation (3a) and Equation (3b) as follows:

Table 6—Models for established thresholds of reaction: median *in situ* E-field thresholds[a, b]

Reaction	E_o pk (V/m)[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	6.15	0.149	3350
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 [B75].
[c]*(V/m-pk)* refers to the temporal peak of the electric field.

$$E_i = E_0 \qquad \text{for } t_p \geq \tau_e \tag{3a}$$

$$E_i = E_0\,(\tau_e/t_p) \quad \text{for } t_p \leq \tau_e \tag{3b}$$

where

t_p is the phase duration of the E_i waveform

Alternatively, the limits can be determined in terms of sinusoidal frequency as shown in Equation (4a), Equation (4b), and Equation (4c):

$$E_i = E_0 \qquad \text{for } f \leq f_e \tag{4a}$$

$$E_i = E_0\,(f/f_e) \quad \text{for } f \geq f_e \tag{4b}$$

$$f_e = 1/(2\tau_e) \tag{4c}$$

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Relationship (4c) has been determined using a theoretical model of myelinated nerve (Reilly [B75]). Because of the nonlinear electrodynamics of excitable tissue, Equation (4c) differs from linear systems for which a relationship $\tau = 1/(2\pi f)$ would be anticipated.

Nerve excitation thresholds follow a U-shaped curve, with a low-frequency upturn at about 10 Hz and a high frequency upturn at a frequency f_e. The plateau between the upper and lower transition frequencies is the rheobase. Theoretical models suggest that the strength-duration time constant and upper transition frequency are related by $f_e = (2\tau_e)^{-1}$ (Reilly [B75], [B77]; Reilly and Diamant [B79]). The low-frequency upturn occurs for *in situ* sinusoidal waveforms initiated at a zero crossing because the slow rate of rise of the sinusoid allows the nerve to accommodate to the stimulus—a feature absent in the square wave stimulus or the sinewave initiated at a peak. To allow for worst-case conditions, the induced field waveform is assumed to be initiated at a peak. Because the induced field is proportional to the derivative of the environmental field at frequencies affecting this standard, this assumption is equivalent to assuming an environmental field initiated at a zero crossing. Above f_e, thresholds converge to a slope that is proportional to frequency.

For a given stimulus duration, a monophasic square-wave current provides the lowest threshold of electrostimulation. Brief biphasic current wave shapes in general have higher thresholds of excitation. The increase in threshold due to a biphasic current reversal becomes greater as the phase duration becomes shorter (i.e., as the frequency content of the event becomes higher). However, for repeated biphasic waves (e.g., a repeated sinusoid), thresholds converge to a value that is approximately that for a single monophasic square wave of the same phase duration (Reilly [B75]). Consequently, thresholds pertaining to monophasic square-wave stimuli, which establish a lower limit, have been applied to biphasic waves with the same phase duration. For a single biphasic event of brief duration the excitation threshold may be higher than that for a monophasic stimulus, and therefore this approach is conservative. However, in the frequency regime of this standard, the degree of conservatism is small.

6.1.1 Nerve excitation

Excitation of nerve and muscle requires depolarization of the membrane resting potential by about 15–20 mV—the exact amount depends upon the stimulus waveshape and other factors. In the region of a locally constant electric field, excitation is initiated where a nerve is terminated, or undergoes a rapid bend, such as may occur at a motor neuron end plate or at sensory receptors (Reilly [B71], [B75]). Under these conditions the threshold of excitation is inversely proportional to the diameter of the nerve axon.

In this standard the assumption has been made that the fiber diameter is at the outer limit of the distribution of fiber sizes found in humans. Accordingly, a maximum diameter of 20 μm is assumed for a peripheral nerve and 10 μm for a CNS neuron. Theoretical models predict E_o = 6.15 V/m and 12.3 V/m for stimulation of 20- and 10-μm nerve fibers, respectively, and τ_e = 128 μs for either fiber size (Reilly [B75]).

These values correspond well to experimental data. Median experimental values of τ_e with magnetic stimulation are reported in the range 146–152 μs (Barker et al. [B4]; Bourland et al. [B13]; Mansfield and Harvey [B59]); although larger values have also been reported (Bourland et al. [B16]; Havel [B39]; Nyenhuis et al. [B66]). Values of τ_e with contact current stimulation encompass a fairly wide range that includes the values observed with magnetic stimulation.

To determine basic restrictions, it is conservative to assume a small value of τ_e, rather than a large one. Consequently, Table 6 adopts a value of τ_e = 149 μs as suggested by an average of the lower experimental values mentioned above. The theoretical value of E_o = 6.15 V/m is considered a median within a distribution of thresholds in healthy adults. Although adequate statistical data is lacking, sufficient data on E_o is available to suggest that the assumption is reasonable. Where the induced E-field could be determined, rheobase for pulsed magnetic stimulation of the forearm was found to be 5.9 V/m (Havel et al. [B39]). In addition, an underlying neural excitation assumption of 6.15 V/m correctly reproduces the distribution of let-go current thresholds in adults (Sweeney [B94]). Furthermore, thresholds of excitation with pulsed magnetic

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stimulation calculated with E_o = 6.15 V/m are reasonably consistent with experimentally determined thresholds (6.3).

The most sensitive means of exciting skeletal muscle is via electrostimulation of the motor neurons that innervate it. Consequently, thresholds for muscle stimulation follow those for nerve excitation. An exception to this occurs with cardiac stimulation, as described below.

6.1.2 Cardiac excitation

Cardiac excitation, which refers to electrical stimulation of a contraction (systole), follows strength-duration and strength-frequency laws like those for nerve excitation, except with much greater values of τ_e (smaller values of f_e). Experimental data demonstrate that τ_e depends on the focality of the stimulus. For focal stimuli, as with a small electrode near the excitable tissue, time constants can be much smaller than when the stimulus is more diffuse, as it would be for magnetically induced *in situ* electric fields. An S-D time constant τ_e = 3 ms has been assumed, which applies to large contact electrodes or diffuse stimulation of cardiac tissue; E_o = 12 V/m has been assumed as a median rheobase for excitation based on experimental data (Reilly [B73], [B75]).

Cardiac excitation is not necessarily hazardous, although ventricular fibrillation (VF) is a serious life-threatening condition. Minimum thresholds for VF typically exceed those for excitation by a factor of 50 or more. However, if the heart is repeatedly excited, the VF threshold drops such that the margin between VF and excitation thresholds may be reduced to a factor as little as two if the stimulus is applied during the vulnerable period within the cardiac cycle.

Cardiac excitation would not be an exposure issue under most circumstances since with exposure of the torso the limits on peripheral nerve excitation would prevail. However, particular circumstances of nonuniform exposure that result in strong induced fields around the heart could conceivably require the application of the cardiac excitation criterion.

6.1.3 Synaptic activity alteration

Whereas the nerve cell requires membrane depolarization of approximately 15–20 mV to initiate an action potential, synaptic processes can be affected by altering the presynaptic membrane potential by less than 1 mV, and possibly as little as 60 μV, as with electrical stimulation of synapses in the retina (Knighton [B53], [B54])—a factor 250 times lower than minimum neural excitation thresholds. Consequently, the synapse is a potentially sensitive site for neural interaction with applied electrical stimuli. An important property of the synapse is that a relatively small change in presynaptic potential can have a much larger percentage change in postsynaptic potentials (Katz and Miledi [B50]). Since the postsynaptic cell sums the presynaptic inputs from several cells, a small change in presynaptic potential can have a significant postsynaptic effect, and can be either inhibitory or excitatory, i.e., could result in the excitation of a neuron that would otherwise not have been excited, or could inhibit excitation of a neuron that would otherwise have been excited.

An example of a synaptic polarization effect is attributed to the phenomenon of electro- and magneto-phosphenes, which are visual effects resulting from electric currents or magnetic fields applied to the head (Adrian [B2]; Barlow [B5], [B6]; Baumgart [B7]; Bergeron et al. [B10]; Budinger et al. [B19]; Carstensen [B21]; Clausen [B24]; Lövsund et al. [B57], [B58]; Silny [B92]). Experimental evidence suggests that phosphenes result from modification of synaptic potentials in the receptors and neurons of the retina (Knighton [B53], [B54]; Lövsund et al. [B57]), rather than excitation of the optic nerve or the visual cortex, although visual sensations with stimulation of the visual cortex have been demonstrated with much stronger stimuli (Brindley and Lewin [B17]; Brindley and Rushton [B18]; Ronner [B83]).

Using data from magnetophosphenes (Lövsund et al. [B57], [B58]) the corresponding induced E-field in the head at the most sensitive frequency tested (20 Hz) is 0.079 V/m-rms as calculated with an ellipsoidal model

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of the head (see Annex B). At the retina, where the electrical interaction is thought to take place, the calculated field is 0.053 V/m-rms, which is consistent with the current density threshold of 0.008 A/m^2 at the retina determined for electro-phosphenes (Lövsund et al. [B58]) assuming the conductivity of the brain is 0.15 S/m. The internal E-field corresponding to phosphene perception at the optimum frequency is a factor of 100 or so below rheobase thresholds for neural stimulation.

Experimental strength-duration data show that τ_e for phosphenes using electrodes on the temples is approximately 14 ms (Baumgart [B7]; Bergeron et al. [B10]) and for electrically evoked potentials in the frog's eye, τ_e is in the range 14–36 ms (Knighton [B53], [B54]). These values are consistent with the phosphene data described above, but are about 100 times greater than corresponding values for peripheral nerves.

Relatively few data exist on synaptic polarization effects by applied electric fields. Considering this dearth of data, reasonable assumptions are made based on the available synaptic effects experimental data and on assumed parallels with nerve excitation properties. One class of these properties concerns strength-duration and strength-frequency characteristics. An average strength-duration time constant for synapse effects is τ_e = 25 ms. Using the relationships noted for nerve excitation, a strength-frequency constant of f_e = 20 Hz is expected above which *in situ* electric field thresholds should rise. This rise is indeed observed in the case of electrophosphene thresholds, although the rate of rise is greater than that observed with nerve excitation (Adrian [B2]; Clausen [B24]). Magneto-phosphene strength-frequency curves reported by Lövsund and colleagues ([B57], [B58]) show a minimum at 20 Hz, and rising thresholds at lower frequencies, in accord with electrophosphene data. Thresholds above 20 Hz vary somewhat with the experimental parameters (background illumination and wavelength, subject visual acuity). Considering electro- and magneto-phosphene strength-frequency and strength-duration curves in total, it is reasonable to adopt a threshold curve similar to that found in electrostimulation of nerve and muscle, but with a much lower strength-frequency constant (or equivalently, a larger strength-duration time constant), and with lower rheobase. Additional study of CNS synaptic interaction effects is needed to clarify these assumptions.

Frequency sensitive thresholds for phosphenes have been experimentally tested only to a maximum frequency of about 75 Hz. The Subcommittee makes the conservative assumption that synaptic polarization thresholds follow a frequency-proportional law above 20 Hz to a frequency of at least 760 Hz (above which peripheral nerve excitation limits dominate the magnetic field MPEs).

In connection with phosphene threshold experiments, Lövsund and colleagues ([B57], p. 330) state: “Virtually all the volunteers noted tiredness and some reported headaches after the experiment. Some experienced afterimages which were generally of only short duration following exposure to the magnetic field. In one case, however, they persisted up to ten minutes after the experiment. Individual volunteers reported spasms of the eye muscles, probably arising from stimulation by the field.” These findings were similar to those of Silny [B92], who reported headaches, indisposition, and persistent visual evoked potential (VEP) alterations at flux density levels above phosphene thresholds, but still well below nerve excitation thresholds (by a factor of 23).

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 discussed previously.

The ability of sub-excitation fields to alter neuronal response has also been reported after exposure of hippocampal slices from the rat brain to magnetic fields (Bawin et al., [B8, B9]) in which induced E-field intensities were as low as 0.75 V/m peak—a factor of 16 below the threshold of 12.3 V/m for excitation of a 10-μm neuron. The rate of maze learning in living mice was significantly reduced by exposure to flux densities at and below 0.75 mT at 50 Hz (Sienkiewicz et al. [B90], [B91]). Although the cited studies did not

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establish a synaptic mechanism, they do support the view that CNS effects, including adverse ones, are possible well below thresholds of excitation of brain neurons.

The spinal cord also contains synapses. Spinal functions are important to the organism (e.g., control of posture; reflex activity). Tests have been conducted with human subjects whose torsos were subjected to the strong switched gradient fields of experimental MRI systems (see 6.1.1 and 6.3.2). Perception was sometimes preferentially reported in the small of the back at stimulus levels corresponding to nerve stimulation thresholds in accord with expectations from an elliptical induction model (see 6.3.2 and Annex B). These tests showed no observable effects below the neural threshold for perception. The lack of an observable effect below electrical perception thresholds suggests one of three possible explanations. One is that spinal synapse interactions did occur, but they were imperceptible to the subject. Another is that the induced field in the spinal column was below synapse interaction thresholds, even though the levels just outside of the spinal column were roughly two orders of magnitude above synapse thresholds. A third is that stimulation thresholds are significantly greater than what has been assumed for synaptic effects in brain neurons (Table 6).

Considering that the Subcommittee could find no data to suggest observable effects from stimulation of the spinal cord at the levels attributed to synapse thresholds, protection in this standard is focused on the brain, rather than the spinal cord.

6.1.4 Averaging time

The rms metrics specified in Table 1, Table 2, Table 3, Table 4, and Table 5 require the specification of an averaging time. For sinusoidal stimulus waveforms, thresholds of nerve excitation evaluated at half-cycle increments oscillate between gradually falling maxima at odd numbers of half cycles, and minima at even number of half cycles, and converge to a single minimum threshold at about 1.3 ms of stimulus duration (Reilly [B75]). The time constants of excitation threshold versus duration for muscle and nerve synapse stimulation exceed that for nerve stimulation by factors of 20 and 168, respectively (Table 7). Consequently, a measurement averaging duration of 200 ms ($\cong 168 \times 1.3$) would encompass the maximum integration duration needed to characterize minimum nerve, muscle, and synapse excitation thresholds. For sufficiently low frequencies, the variation of threshold with the number of cycles above one is trivial, and a measurement averaging time of a few cycles appears adequate. For frequencies below 0.1 Hz, a maximum averaging time of 10 seconds (one cycle) is considered adequate.

6.1.5 Spatial averaging

When determining compliance with the basic restrictions (Table 1), an important parameter is the averaging distance, d_a, over which the *in situ* electric field should be measured. A related question is the required distance over which the electric field must exist for efficient electrostimulation. For cases of practical interest involving unintended electrical exposure, the most sensitive means of exciting a nerve fiber is via an *in situ* electric field oriented with the long axis of the nerve fiber, and acting at its terminus (Reilly [B75]). An exception to this statement might occur when a small stimulus electrode is situated near the nerve, but such cases would normally be found only in medical applications, rather than chance electrical encounters.

The relationship between the threshold of excitation and the distance over which the field exists (d_e) has been determined using a nonlinear model of a myelinated nerve (Reilly and Diamant [B80]). With this model, a minimum threshold was obtained with d_e of seven or more internodal spaces. With d_e of one internodal space, the threshold was twice the minimum value. With d_e = 2, 3, 4, and 5 internodal spaces, the threshold exceeded the minimum value by 34, 14, 7, and 3%, respectively. For a nerve axon diameter of 20 μm (the size assumed in this standard for peripheral nerves), the internodal distance is 2 mm. If an averaging distance (d_a) of 5 mm is used, and assuming a field just at the threshold of excitation corresponding to d_e, the measured average field with $d_e \leq 2$ internodal spaces would be within 19% of the basic restriction value (Table 1). For larger d_e and with a corresponding threshold field, the measured average field over 5 mm approaches the basic restriction value within a few percent. It appears that 5 mm

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represents a reasonable averaging distance, which is neither overly conservative nor permissive. Consequently, the Subcommittee specifies that the *in situ* electric field be determined as the average over a distance d_a = 5 mm, which can be readily determined from the potential difference at a spacing of 5 mm.

6.2 Adverse reaction criteria

The purpose of basic restrictions and MPE limits is to avoid adverse reactions, not just perceptible ones. Aversive or painful electrostimulation is considered an adverse effect. Painful sensations from magnetic stimulation of peripheral nerves are reported at multiples above perception thresholds of 1.3 (Budinger et al. [B20]), 1.6 (Bourland et al. [B15]), and 1.48 (Nyenhuis et al. [B67]; Schaefer et al. [B88])—an average multiple of 1.45. The mean threshold for intolerable pain was observed at a perception multiple of 2.05 (Schaefer et al. [B88]). The median rheobase threshold for painful sensations is taken as $E_o = 6.15 \times 1.45 =$ 8.92 V/m (peak). Based on a log-normal probability model of human perception thresholds of electrical stimuli (see 6.8), a conservative estimate of a one-percentile pain reaction threshold for healthy adults would be a factor of 3 below the median, resulting in a rheobase of 2.97 V/m.

In the case of contact current stimulation, unpleasant and painful sensations are elicited at greater multiples above perception than with magnetic stimulation. Based on experimental data from several sources (Reilly, [B75], Table 7.3), painful stimulation is estimated to occur at a multiple of 2.4 above the perception threshold; unpleasant sensations are estimated to occur at a multiple of 1.7; the ratio of pain to unpleasantness thresholds is about 1.4.

That smaller pain-to-perception ratios are found with magnetic stimulation than with contact current stimulation may be explained by the fact that in magnetic stimulation, the distribution of induced current varies only gradually with respect to body dimensions. Consequently, at a field level where some neurons first begin to be excited, a small increase in the field may excite neurons over a large area. If pain is magnetically induced in some area of the body, it is likely to be in an extended area. In contrast, cutaneous stimulation is more focal. Suprathreshold stimulation in a large area may be more painful than in a small area, and that might account for the differences in pain-to-perception ratios between magnetic induction and small-area contact current.

Cardiac excitation is considered adverse. Although not necessarily life threatening in itself, it is potentially dangerous if it is repeated in close succession, such as can be the case with sinusoidal or repeated pulse stimulation of the heart (see 6.1.2).

With synaptic effects, the Subcommittee treats any alteration of brain activity as a result of electrical stimulation of brain neurons via the induced *in situ* electric field as a potentially adverse outcome. Such conservatism is motivated by the adverse reactions (tiredness, headaches, muscle spasms, persistent after-images) reported in laboratory experiments using magnetic field exposures near the threshold of synapse effects (see 6.1.3).

With magnetohydrodynamic effects and forces on charges due to rapid body motion in strong static and quasi-static fields, a variety of biological effects have been observed (see 6.4). In light of these observations, adverse reactions are assumed at 1.06 T-rms (1.5 T-peak) in 50% of human subjects at frequencies below 1 Hz, which possibly include nausea, vertigo, and taste sensations associated with head movement.

6.3 Threshold limits for magnetic field exposure

To derive an environmental magnetic field from allowable *in situ* E-field magnitudes, it is necessary to apply an induction model. Traditional methods used to predict whole body energy absorption during magnetic field exposure include the use of ellipsoid shapes arranged to mimic an animal or man (Reilly [B72]). During the past several years, high-resolution anatomical models have been developed to enhance the capability to predict localized energy absorption, such as within a single organ or part of an organ.

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6.3.1 Detailed anatomical induction models

The development of the high-resolution models has enhanced tremendously the understanding of energy absorption during electromagnetic field exposure. However, this development has also revealed several inadequacies in present knowledge regarding dosimetry. Hurt and colleagues [B41] demonstrated how variability in published permittivity values influence specific absorption rate (SAR) calculations. Although SAR values are pertinent only at the higher frequencies, the influence of permittivity values on predicted induced internal fields produced by the lower exposure frequencies should also be determined. Mason and associates [B60] evaluated the influence of voxel size on the predicted energy absorption during electromagnetic field exposure. Increasing voxel size could either increase or decrease the predicted amount of energy absorbed within a voxel. In general, there was usually a decrease in the amount of energy absorbed, but this was not always the rule. It appears that the better solution is to use the highest-resolution model available, and then average the amount of energy absorbed amongst the voxels. However, even if a model has a small voxel size, this does not necessarily imply that the high-resolution anatomy or separation of anatomical components has been adequately incorporated.

A comparison of induced electric field calculations obtained by several investigators using a similarly detailed anatomical model and similar numerical techniques (Dawson and Stuchly [B28]; Dimblylow [B30]; Gandhi [B37]) showed differences of over 5:1 in the maximum field in critical organs; organ averages were usually reasonably consistent, although differences as great as 2:1 were noted. Since the basic restrictions of this standard depend on the maximum field in particular organs, large variations in reported maximum values make it difficult to apply presently available detailed models to standards.

An important missing element in high resolution modeling is validation. Simply producing a model is insufficient for declaring that the results produced by using this model are accurate. Substantial laboratory testing on biological tissue should be incorporated into any model development. Comparison of the theoretical and empirical results and the subsequent refining of a model are essential in order to earn the credibility essential when using these models to establish or revise exposure standards.

6.3.2 Ellipsoidal induction model

Limits on environmental magnetic fields in this standard have been based on an ellipsoidal model of the head and torso of a large individual, with uniform conductivity, and a constant magnitude and relative phase of the field over the body dimensions as described in Annex B. In all calculations, a worst-case assumption has been made for the direction of the field relative to the body.

Using this model, an *in situ* field of 6.15 V/m (the presumed median nerve excitation threshold among subjects) has been calculated to be induced in the periphery of the torso with whole-body exposure to *dB/dt* = 37.5T/s (see Annex B and Table B.1). That theoretical value applies to conditions of exposure that minimize the excitation threshold, namely: a very large adult; constant magnitude, direction, and relative phase of the incident field over the dimensions of the body; a monophasic square-wave shape of the *in situ* electric field. In most cases, experimental conditions deviate from the optimal parameters resulting in greater thresholds than the minimum ones.

One of the cited optimal conditions was a monophasic square-wave shape for the induced electric field. Note that the *in situ* field follows the waveform of the time derivative of flux density, *dB/dt*, which is necessarily biphasic for a magnetic pulse; the mean is zero if the rise and fall magnitudes of flux density are equal, although the rise and fall times need not be equal. If the induced waveform is such that the phase reversal is either delayed or is gradual, then the threshold can be effectively the same as would apply to a monophasic waveform.

The conservatively derived theoretical value of 37.5 T/s may be compared with experimental thresholds conducted with pulsed magnetic field exposure of the human torso in MRI studies (Bourland et al. [B12], [B13], [B14], [B15]; Budinger et al. [B20]; Cohen et al. [B25]; Mouchawar et al. [B61]; Nyenhuis et al.

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[B66]; Schaefer et al. [B86], [B87]; Yamagata et al. [B98]), as previously reviewed (Reilly [B75], Sect. 9.7). Mean perception thresholds of 60 T/s were reported by two investigators (Budinger et al. [B20]; Cohen et al. [B25]), and a minimum threshold of 45 T/s was reported by another (Bourland et al. [B12]). Higher thresholds were reported by others, but, like the above cited studies, these involved sub-optimum waveforms or conditions not conducive to minimum rheobase values.

Simulated MRI fields used in experiments discussed above varied considerably in amplitude and relative phase over the dimensions of the human torso. The optimum field metric for electrostimulation is not clear when such nonuniformity exists. Recent studies report perception thresholds in terms of the spatially averaged exposure, rather than the spatial peak as in most of the studies mentioned above. Using a spatial average metric, an average rheobase value of the perception threshold was reported at 25 T/s in one study involving 65 subjects (Hebrank [B40]), and 28.8 T/s in another study involving 84 subjects (Nyenhuis et al. [B66]).

Cardiac excitation thresholds using magnetic stimulation have been determined in dogs. Early results (Mouchawar et al. [B62]; Yamaguchi et al. [B99]) indicated *dB/dt* thresholds in excess of what would be predicted from the models used here (Table 7 and Table B.1), although this could be explained by the use of sub-optimum exposure conditions in the cited studies (Reilly [B73]). More recent test results with dogs (Schaefer et al. [B88]) conformed well with the models used in this standard when scaled from animal to human dimensions. It was also established that the addition of a 1.5 T static field to the time-varying excitatory field does not alter cardiac excitation thresholds (Bourland et al. [B16]).

With consideration of theoretical and experimental data, the Subcommittee adopts as median thresholds the peak *dB/dt* ($\dot{B}$) values listed in Table 7. Annex B describes the methods whereby the external field thresholds of Table 7 are derived from the *in situ* parameters of Table 6.

Table 7—Models for established magnetic dB/dt thresholds of reaction: whole body exposure; median thresholds[a]

Reaction	$\dot{B}_o$ - pk (T/s)[b]	τ_e (ms)	f_e (Hz)
Synapse activity alteration, brain	1.45	25.0	20
10-µm nerve excitation, brain	237	0.149	3350
20-µm nerve excitation, body	37.5	0.149	3350
Cardiac excitation	88.7	3.00	167

[a]Interpretation of table as follows: $\dot{B} = \dot{B}_o$ for $t_p \geq \tau_e$; $\dot{B} = \dot{B}_o\,(\tau_e/t_p)$ for $t_p \leq \tau_e$.

Also, $\dot{B} = \dot{B}_o$ for $f \leq f_e$; $\dot{B} = \dot{B}_o\,(f/f_e)$ for $f \geq f_e$.

[b](*T/s-pk*) refers to the temporal peak of the magnetic flux density.

Thresholds are computed from the parameters of Table 7, and as shown in Equation (5a) and Equation (5b) as

$$\dot{B} = \dot{B}_o \qquad \text{for } t_p \geq \tau_e \tag{5a}$$

$$\dot{B} = \dot{B}_o\ (\tau_e/t_p) \qquad \text{for } t_p \leq \tau_e \tag{5b}$$

where

t_p is the phase duration of the $\dot{B}_o$ waveform

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Alternatively, the limits can be determined as shown in Equation (6a) and Equation (6b)

$$\dot{B} = \dot{B}_o \quad \text{for } f \le f_e \tag{6a}$$

$$\dot{B} = \dot{B}_o \, (f / f_e) \quad \text{for } f \ge f_e \tag{6b}$$

Flux density, *B*, listed in Table 8 can be computed from the Table 7 criteria using the relationships for sinusoidal fields as shown in Equation (7) and Equation (8)

$$\dot{B} = \dot{B}_o / (2\pi f_e) \tag{7}$$

$$B_O(rms) = B_o(peak) / (\sqrt{2}) \tag{8}$$

where

$\dot{B}_o$ is the minimum (rheobase) threshold value of *dB/dt*
B_o is the minimum threshold value of *B*.

Median flux density thresholds are computed from Table 8, and Equation (9a) and Equation (9b) as

$$B = B_o \quad \text{for } f \ge f_e \tag{9a}$$

$$B = B_o \, (f_e / f) \quad \text{for } f \le f_e \tag{9b}$$

Table 8—Median magnetic flux density thresholds; whole body exposure[a]

Reaction	B_0 - rms (mT)	H_0 - rms (A/m)	f_e (Hz)
Synapse activity alteration, brain	8.14	6.48×10^3	20
10-µm nerve excitation, brain	7.97	6.34×10^3	3350
20-µm nerve excitation, body	1.27	1.00×10^3	3350
Cardiac excitation	59.8	4.76×10^4	167

[a]Interpretation of table as follows: $B = B_o$ for $f \ge f_e$; $B = B_o \, (f_e/f)$ for $f \le f_e$.

Considering the procedures discussed above, it is apparent that the flux density limits in Table 8 are based on the assumed *in situ* limits of Table 6 evaluated at the site of interaction. For instance, the brain exposure limits are based on the estimated field induced in the outer perimeter of the cerebral cortex; cardiac excitation applies to the field induced in the apex of the heart; and peripheral nerve limits are based on the maximum induced field in the periphery of the torso.

6.4 Static or quasi-static magnetic field exposure

Whereas Equation (9b) indicates that flux density thresholds would increase to infinity as the frequency approaches zero, an upper limit on flux density is required to avoid adverse effects from magnetohydrodynamic forces on moving charges within a magnetic field. Such movement is typically

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associated with the vascular system, although observable effects can also result from the rapid movement of the body or eyes within a strong static field. The physical effects are *Hall* voltages or *Lorentz* forces.

With static magnetic fields, reactions under laboratory conditions include a 17% increase in human cardiac cycle length at 2 T (Jehesen et al. [B49]). The authors gave the opinion that the observed effect is probably harmless in healthy subjects, but that its safety in dysrhythmic patients was not certain. Other observations included a 0.2–3% change in blood velocity between 1–10 T (Dorfman [B31]; Keltner [B52]). A host of adverse effects were noted at 1.5 T, including: vertigo, difficulty with balance, nausea, headaches, numbness and tingling, phosphenes, and unusual taste sensations. Much more marked reactions were noted at 4 T (Schenck et al. [B89]). Other effects include benign enhancement of the cardiac T-wave in rats at 4 T (Gaffey and Tenforde [B36], Tenforde et al. [B95]).

The studies of Schenck and colleagues report adverse effects in a significant number of subjects at 1.5 T, which the Subcommittee adopts as a median threshold for adverse effects. A peak value of 1.5 T is associated with a slowly varying sinusoidal field of 1.06 T-rms. A statistical model has been assumed for the distribution of thresholds that follows the same lognormal distribution found in other electrical thresholds (see 6.8). Consequently, at a factor of 3 below the median, namely, 353 mT (the value listed in Table 2 for the lowest frequencies), the affected population of sensitive individuals is estimated to be less than 1% of exposed individuals. For the general public the Subcommittee applies an additional safety factor of 3, which leads to the value of 118 mT (as listed in Table 2).

6.5 Nonsinusoidal or pulsed fields

The basic restrictions and MPE levels in Table 1, Table 2, Table 3, Table 4, and Table 5 are expressed as a function of frequency assuming a sinusoidal exposure waveform. In many practical situations, however, the applicable waveform may not be sinusoidal, such as with a waveform having harmonic distortion, or with pulsed waveforms. Subclause 5.2.4 expresses tests for determining the compliance of a nonsinusoidal waveform (pulsed or mixed frequency) based on previous studies (Reilly [B74], Reilly and Diamant [B79]). One of these tests is required to be met in addition to satisfying the rms limits of Table 1 or Table 2.

The criteria in 5.2.4.1 are based on the temporal peak and phase duration of either the *in situ* field (or contact current), or the derivative of the environmental field. Alternatively, Equation (2) in 5.2.4.2 uses Fourier components of the test waveform. Since criteria in either subclause are conservative, either may be used to test for compliance. The choice may be dictated by the relative ease of obtaining the requisite data to implement the test (Fourier components versus temporal peak and phase duration).

In some cases the compliance tests may be overly conservative. Such cases may occur when the waveform appears as a low frequency wave on which is superimposed a short duration impulse. The degree of conservatism would increase as the impulse becomes shorter in duration, and greater in amplitude. A more precise test would require evaluation of the threshold of a specific waveform with a neural excitation model, such as the one used in the cited study (Reilly and Diamant [B79]).

The maximum frequency used in Equation (2) is 5 MHz, which is outside the limits of this standard. However, it is possible that a particular waveform does not respect the frequency division between this standard and IEEE Std C95.1 that treats higher frequencies. Since it is not meaningful to truncate the summation of Equation (2) at 3 kHz, the summation is shown as applying to the maximum frequency of demonstrable electrostimulation.

6.6 Exposure to environmental electric fields

Since environmental electric fields induce *in situ* electric fields and body currents, it might seem logical to conclude that the induced field should be limited so as to preclude direct electrostimulation effects. In practice, however, contact current and spark discharge criteria (indirect electrostimulation) limit

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environmental electric fields to values significantly lower than what is required to directly induce *in situ* electric fields at the levels in Table 1 and Table 6. For example, the basic restriction for the *in situ* electric field in the brain is 17.7 mV/m at 60 Hz for the general public (Table 1). To induce this field in a grounded, erect person would require an environmental field of about 59 kV/m (Carstensen [B22]). Considering that the undisturbed field is enhanced at body surfaces—18 times, for example, on the head of an erect person (Kaune [B51]), and even greater enhancements are possible on extended fingertips—parts of the body could be in a state of corona at environmental field levels necessary to induce the cited E-field within the brain.

Indirect stimulation effects occur through charge transfer between a person and a conducting object within the field. With sufficiently strong fields, an individual can perceive spark discharges just prior to the moment of direct contact and just after breaking contact with conducting objects that are well insulated from ground. It is also possible to perceive current through direct contact with such objects.

The contact current component, I_c, for an erect person touching a grounded conductor in a vertically polarized electric field is shown in Equation (10) (Reilly [B75])

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

where

h is the height of the person
f is the frequency of the field
E is the environmental field strength

For fields with frequencies within the limits of this standard, in which the environmental field magnitude varies over the area that would be occupied by the body, the field strength in Equation (10) may be replaced with the average environmental field over the area in which the body is placed (Deno and Zaffanella [B29]; Kaune [B51]).

Exposure limits on environmental electric fields in Table 4 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 ground (rubber sole shoes, standing on an insulated surface, etc.). The limits may not protect grounded individuals from adverse electrostimulation when touching large conductive objects that are insulated from ground.

The field limitations in Table 4 that provide protection against adverse contact current vary in inverse proportion to frequency. If this law were to extended to zero frequency, the electric field limit would approach infinity. An upper limit is placed on the maximum permissible E-field to limit the probability of an adverse reaction to a spark discharge.

The maximum permissible field in Table 4 is 5 kV/m for the general public. It is estimated that spark discharges would be painful to approximately 7% of adults who are well insulated and who touch a grounded object within a 5 kV/m field. Unpleasant spark discharges can also occur when a grounded person touches a large conductive object that is well-insulated from ground situated within a strong field. It is not possible to absolutely protect against all possibility of adverse stimulation without mitigating the induced charge on the object when very large (or long) objects are situated near sources that produce electric fields that are very extended spatially, such as is the case with high-voltage power transmission lines. For instance, one might postulate a long fence wire on insulated posts running parallel to a high-voltage transmission line. In such cases, it is preferable to restrict electrostimulation by properly grounding the conducting object (as stated in other safety codes), rather than by limiting the electric field to an impractically small level.

In the controlled environment where the MPE is limited to 20 kV/m, painful spark discharges, but not contact currents, can be readily encountered at the stated limit for an insulated person at ground level

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touching a grounded conductive object. In such strong fields, workers should limit the probability of painful spark discharges by appropriate use of protective clothing, grounding measures, contacting techniques, or other work practices that consider these environmental electric field effects. In the controlled environment, conductive suits can be worn that shield the body from high environmental electric fields, thereby greatly reducing indirect electrostimulation. Currents conducted to the body of individuals wearing protective clothing shall not exceed those in Table 5.

Power line rights-of-way fall somewhere between the definitions of “controlled” and “uncontrolled” environments for the general public in that public activity can be circumscribed by the utility, but that public access is often allowed for the public benefit. Consequently, this standard specifies a limit of 5 kV/m for the general public in regions off the right-of-way, but allows an intermediate field of 10 kV/m within the right-of-way under normal load conditions. (If the powerline right-of-way conforms to the requirements of a controlled environment, then the controlled environment limits apply.) Experimental data using spark discharge stimuli on human subjects (Reilly [B75]; Reilly and Larkin [B81]) can be applied to this exposure. In a field of 10 kV/m, about 50% of adult subjects (1.8 m tall) who are well insulated from ground would experience painful discharges when contacting a grounded conductor. The stated probability would increase with taller subjects and decrease with shorter ones. It is also decreased by imperfect insulation of the person with respect to ground.

Maximum electric fields permitted within and off power transmission line rights-of-way are subject to limitation from other agencies or requirements, such as the U.S. National Electrical Safety Code and other electric utility regulations. The National Electrical Safety Code® (NESC®) (Accredited Standards Committee C2-1997) specifies a safety limit of 5 mA short circuit current (i.e., the current into a low-impedance connection to earth) from objects within the electric field of a high-voltage transmission line. The intent of this provision is to limit contact currents to the “let-go” level of a few percent of sensitive children under worst case conditions, rather than to avoid aversive or painful perception of contact current or spark discharges.

In the absence of indirect stimulation, environmental E-fields can sometimes be perceived through vibration of body hair caused by the interaction of the field and charged hair follicles. With a sufficiently strong field the sensation can be annoying to some people. For instance, at 20 kV/m in an outdoor environment, 50% of standing adults can perceive a 60 Hz field, and about 5% will consider the sensation annoying (Deno and Zaffanella [B29]; Reilly [B69]). Although 20% of subjects perceived a 60-Hz electric field at 9 kV/m, less than 5% could detect electric fields of 2 or 3 kV/m (Reilly [B69]). With hands raised above the body, the median perception threshold is 7 kV/m.

When an exposed individual is not within reach of a grounded conducting object, such as with a live power line worker in an insulated bucket, the maximum exposure limits in Table 4 may not apply. In such cases, the magnitude of contact current and spark discharges will be determined by the potential difference between the individual and the touched object, and their capacitances. The Subcommittee recommends adherence to the limits of Table 4 for the general public, however, the limits of Table 4 may be exceeded in controlled environments in which workers are not within reach of grounded conducting objects. The Subcommittee does not have a specific recommendation at this time for this situation. Regardless of the size and proximity of conducting objects that may be touched by the exposed individual, an absolute upper limit on acceptable exposure will be determined by the need to prevent corona on body surfaces. It is unlikely that exposures in excess of 30 kV/m (undisturbed field) would be acceptable on any exposed body part.

6.7 Static or quasi-static electric fields

The maximum permissible environmental electric field has been capped to limit the probability of painful spark discharges. This limit could, in principle, be extended to arbitrarily low frequencies since even a single discharge can be painful. However, at a sufficiently low frequency, the time constant, τ_h, at which a human can maintain a charge will begin to limit the magnitude of the induced charge. The time constant is given by

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the product of the capacitance and resistance to ground of the person. For example, consider a resistance of 1000 MΩ, which is applicable to 10% of people with normal footwear on dry ground (Reilly [B70], [B75]), and a capacitance of 150 pF. These assumptions result in a time constant of 150 ms, which is equivalent to a frequency of 1 Hz below which the induced voltage in a given field would fall, and the permissible exposure could rise. However, for people on well-insulated surfaces, longer time constants would be possible. The validity of this observation is apparent considering that one may experience an unpleasant carpet spark a second or more after the charge has been acquired.

These observations may be applied to the standards of Table 4 as follows. For leakage resistance of 1000 MΩ, the allowable maximum limits below 1 Hz could be increased approximately in inverse proportion to frequency; for greater resistances, the applicable frequency would become lower.

6.8 Statistical variations in thresholds of reaction

Large variations in electrical thresholds are observed from one person to another. The statistical distribution of electrical reaction thresholds is typically represented by a *lognormal* distribution, i.e., one in which the logarithm of a statistical variate has a normal distribution. The mean of a lognormal distribution always exceeds the median. The mean-to-median ratio, ρ, is expressed as shown in Equation (11) (Hastings and Peacock [B38])

$$\rho = \exp\left(\frac{\sigma^2}{2}\right) \tag{11}$$

where

σ is the variance of the natural logarithm of the statistical variate.

For a distribution in which the ratio of 50% to 1% values equals three, the mean-to-median ratio is 1.12, i.e., the mean exceeds the median by 12%. This relationship is useful in cases where an experimental mean is given, rather than a median.

Experimental thresholds correspond well to the lognormal distribution in many instances of electrostimulation, although it is often necessary to replot published data on lognormal coordinates to demonstrate this. The lognormal distribution is found in: human perception of contact current (Larkin et al.[B56]); bovine perception of contact current (Reinemann et al. [B82]); human “let-go” thresholds (Dalziel [B26]); human perception of electric fields (Reilly [B69]); human perception of and pain from time-varying magnetic fields (Nyenhuis et al. [B67]); human electroconvulsive therapy (ECT) seizure thresholds (Weaver and Williams [B97]); and cardiac VF thresholds in dogs (Reilly [B75]).

A lognormal slope can be expressed as the ratio of the median to the one-percentile thresholds. Approximate slope parameters from experimental data can be summarized as: human perception of contact current on the forearm: 3.0; human perception, fingertip: 2.0; VF thresholds, dogs: 2.1; bovine contact current perception: 2.3; human ECT seizure thresholds: 2.0; human perception of time varying magnetic fields: 1.9. It can be seen that a slope parameter of 3 represents an observed maximum slope applied in this standard, although a more typical condition would have a slope parameter of about 2.

Table 9 provides examples of log normal models (medians normalized to 1.0) applicable to sensory stimulation of the forearm of healthy adult humans, and to ventricular fibrillation (VF) in healthy dogs (Reilly [B75]). Experimental data for fingertip perception more closely follow the VF values. Compared with data from healthy animals, a much broader distribution of VF thresholds has been reported for direct electrode contact to the hearts of human patients undergoing open-heart surgery for valve replacement (Watson et al. [B96]). Thresholds for persons in a pathological state or under drug treatment have not been otherwise tested.

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Table 9—Normalized distribution of electrical reaction thresholds using lognormal model for healthy adult population (male and female)[a, b]

Percentile rank (%)	Threshold multiplier perception and pain	Threshold multiplier ventricular fibrillation
99.5	3.45	2.33
99.0	3.11	2.14
95.0	2.24	1.67
90.0	1.85	1.51
75.0	1.40	1.24
50.0	1.00	1.00
25.0	0.72	0.80
10.0	0.54	0.66
5.0	0.45	0.60
1.0	0.32	0.47
0.5	0.29	0.43

[a]Perception distribution based on human experimental data for arm contact. Ventricular fibrillation distributions from healthy dog hearts.
[b]Source: Reilly [B75].

It is tempting to extrapolate the distribution model of Table 9 to arbitrarily small percentile ranks. However, experimental evidence is insufficient to support extrapolation much below the rank of about 1% due to limitations in the numbers of subjects represented in available experimental data. The Subcommittee adopts a factor of three to convert median thresholds to a sensitive individual. This would encompass at most one percent of most sensitive individuals, but generally a much smaller percentile would be affected for most reactions treated in this standard.

Variations in thresholds from one individual to another are not well understood. The only significant physiological parameter that has been correlated with electrical thresholds is body size and related parameters, such as gender and age (Larkin et. al. [B56] and Reilly [B75], [B81]). The correlation is such that small individuals tend to have lower thresholds. A body size relationship is found in sensory reactions, let-go thresholds, and ventricular fibrillation. Experimental evidence indicates that thresholds of pain in humans and VF thresholds in animals vary approximately with the square-root of body weight, although other relationships have been proposed (Reilly [B75]). Let-go thresholds in humans vary approximately in proportion to body weight. Consequently, small individuals, especially children, would be most susceptible to electrical stimulation effects. On the other hand, the magnitude of current induced by electric or magnetic fields diminishes with decreasing subject size. And with contact current, the small individual typically has a greater inter-limb resistance than a larger person. Because of these compensating factors, the effect of body size is not expected to be great. Indeed, a study of the relationship between magnetic field perception thresholds and morphological factors (subject gender, girth, weight, and age) demonstrated a lack of significant correlation with any of these factors (Nyenhuis [B67]).

Subclause 6.11.2 provides an example of the application of the lognormal statistical model.

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6.9 Acceptance criteria

6.9.1 Basic restrictions

Maximum permissible exposure levels listed in Table 1 were derived from the median thresholds of Table 6 by applying multipliers that convert from a median threshold of excitation to an adverse reaction threshold with low probability in healthy adults and with an adequate safety factor. Table 10 summarizes multipliers used to derive the basic restrictions: column A lists the reaction under consideration; column B lists the locus of stimulation; column C lists median rheobase excitation thresholds, E_{ot}, from Table 6, but converted from peak to rms values using the conversion E(rms) = E(peak)/$\sqrt{2}$; column D lists multipliers, F_a, applied to column C that convert from a median excitation threshold to a median adverse reaction threshold; column E lists multipliers, F_p, that convert from a median threshold to a low-probability one; column F lists safety factors, F_s, applied to the general public and in the controlled environment, respectively; column H lists rheobase *in situ* fields, $E_{ob} = E_{ot}F_aF_pF_s$, which are the rheobase basic restrictions in Table 1.

Basic restrictions listed in Table 1 are in terms of *in situ* induced electric fields; the mode of induction, however, can be through the action of the environmental magnetic or electric field. In addition to induced electric field specifications, it is also necessary to restrict the *in situ* magnetic field to avoid adverse reactions due to magnetohydrodynamic effects from very low frequency magnetic fields (see 6.4). Table 1 specifies such restrictions below 10 Hz. It is not necessary to specify magnetic field basic restrictions at greater frequencies, because potential adverse effects would be related to the induced electric field, rather than the *in situ* magnetic field itself.

The following paragraphs summarize the rationale for the multipliers appearing in Table 10.

Table 10—Factors for converting median thresholds to MPE values

A	B	C	D	E	F Safety factor (F_s)		G Basic restrictions (E_{ob})	
Reaction	**Locus**	**Threshold E_{ot} (50%) (V/m, rms)**	**Adverse mult. (F_a)**	**Prob. mult. (F_p)**	**General public**	**Contr. environ**	**General public (V/m, rms)**	**Contr. environ. (V/m, rms)**
Synapse alter.	Brain	0.053	1.0	0.333	0.333	1.000	5.89×10^{-3}	1.77×10^{-2}
10-µm neuron excite	Brain	8.70	1.0	0.333	0.333	1.000	0.970	2.90
20-µm neuron pain	Body	4.35 (percept.)	1.45 (pain)	0.333	0.333	1.000	0.700	2.10
20-µm neuron pain	Hands, feet, wrists, ankles	4.35 (percept.)	1.45 (pain)	0.333	1.000	1.000	2.10	2.10
Cardiac excite	Heart apex	8.49	1.0	0.333	0.333	0.333	0.943	0.943

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6.9.1.1 Adverse reaction factor

Pain is considered an adverse response with peripheral nerve excitation. An adverse reaction multiplier of F_a = 1.45 is applied to the nerve excitation threshold to derive a pain threshold (see 6.2). With synaptic effects, brain stimulation, and cardiac excitation, excitation itself is considered adverse as noted in 6.1.2 and 6.1.3; hence the adverse reaction multiplier of F_a = 1.0 is applied to the excitation threshold for these reactions.

6.9.1.2 Probability factor

A probability factor, F_p, is applied to convert from a median threshold to a low-probability one. For a lognormal distribution in which the slope parameter (median-to-one-percentile ratio) is 3, the multiplier of 0.333 applied to the median threshold corresponds to a one-percentile most sensitive subject. Whereas a slope parameter of 3 is observed in some cases (e.g., contact current perception on the forearm), with other reactions of critical application to this standard (magnetic field perception, cardiac VF, brain ECT thresholds), the slope parameter is very close to 2.0 (see 6.8). With a slope parameter of 2, a multiplier of 0.333 applied to the median threshold results in a 0.01% probability rank.

6.9.1.3 Safety factor

A safety factor multiplier of F_s = 0.333 allows for protection of exceptionally sensitive individuals, uncertainties concerning threshold effects due to pathological conditions or drug treatment, uncertainties in the reaction thresholds, and uncertainties in the induction models. In the case of the hands, wrists, feet, and ankles, F_s = 1 for the general public in recognition of the narrow cross sections and preponderance of low conductivity tissue that tend to enhance the *in situ* E-field in these areas in comparison with other areas of the body. Because these regions lack critical function when compared with the vital organs, a greater localized electric field is permitted. In the case of the controlled environment, F_s = 1 for all of the reaction types except for cardiac excitation under the assumption that a small probability of discomfort is acceptable in the controlled environment for some mechanisms, but that cardiac excitation is unacceptable for all individuals. The safety factor F_s = 1 can be justified for the indicated exposures because this standard is based on avoidance of short-term reactions that are immediately apparent to the exposed individual, rather than chronic exposure health effects at sub-perception levels, and where cumulative exposure might be significant. It is assumed that, because the short-term reactions are apparent to exposed individuals, they can remove themselves from the environment, modify their activities, or can take other action to avoid the exposure entirely.

If the safety factor F_s = 0.333 is to be compared with that applied at higher frequencies of IEEE Std C95.1, note that a divisor of 3 applied to the magnitude of the induced field is equivalent to a divisor of 9 in the SAR because SAR is proportional to the square of the induced field.

6.9.2 Maximum permissible exposure levels

Sophisticated computational capabilities may sometimes be required to assess whether basic restrictions are met. Consequently, it is desirable to define MPE values which are reference levels in terms of the environmental field, rather than the induced *in situ* field. The MPEs listed in Table 2 incorporate conservative assumptions such that adherence to them insures that the basic restrictions are not exceeded. However, since the MPEs are conservatively derived, it is possible that one may exceed them and still be within the basic restrictions.

Figure 1 illustrates the derivation of MPE levels for magnetic fields. The figure shows median thresholds of adverse reaction (broken lines), and MPEs (solid lines) with whole body exposure. The MPEs are derived from the minimum adverse thresholds at each frequency, decremented by the appropriate probability and safety factors in Table 10. The curve for synapse alteration has been extended to 1000 Hz. The MPE curves have been derived from the lowest adverse reaction threshold across the frequency spectrum as follows: 0– 0.153 Hz, magnetohydrodynamic effects; 0.153–759 Hz, synapse alteration;

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above 759 Hz, peripheral nerve pain. Note that the MPEs in the controlled environment correspond to low probability reaction thresholds (≤ 1%). The limits applicable to the general public are lower by a factor of three. Table 2 expresses the MPE reference values.

For purposes of demonstrating compliance with this standard, Table 2 and Table 4 shall be considered separately, and not additively. This is because the *in situ* electric field induced by environmental electric and magnetic fields are maximized in disjoint regions of the body under the conditions represented in Table 2 and Table 4.

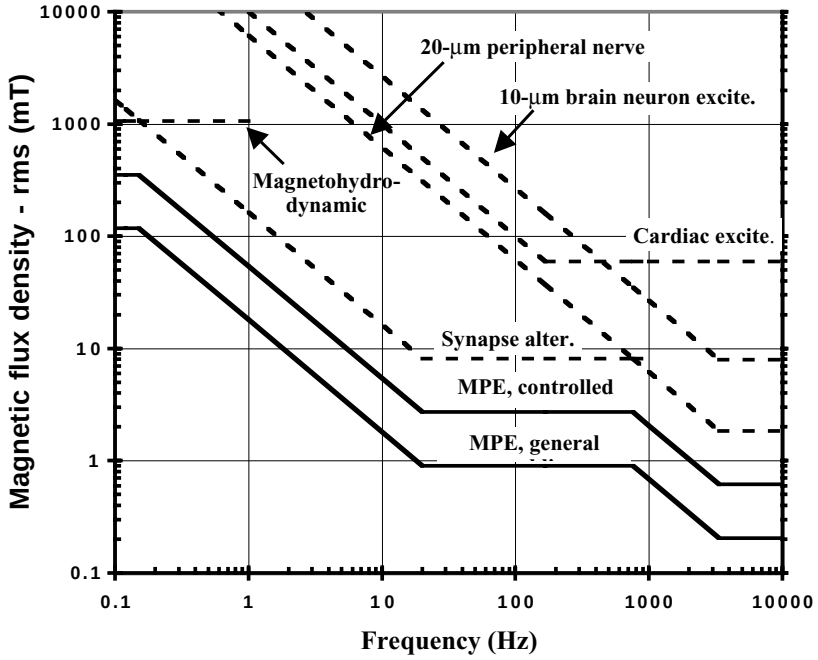


Figure 1— Median thresholds for adverse stimulation from magnetic field exposure (broken lines) and recommended maximum permissible exposure limits (solid lines); whole-body exposure to spatially constant field

6.10 Partial or nonuniform exposure

The limits of Table 2 are designed to avoid adverse reactions with whole body exposure to magnetic fields that are relatively constant in magnitude and relative phase over the entire body. Because the contribution of the *in situ* electric field within the head and torso due to exposure of the arms and legs is not great, the limits also apply to a constant field over only the head and torso. However, when a magnetic field is not constant over the head and torso, a conservative approach for magnetic fields would be to limit the spatial peak of the actual field in accordance with Table 2. It is possible that such an approach might be unduly restrictive. An acceptable alternative would be to limit the external magnetic field such that the *in situ* E-fields do not exceed the basic restrictions of Table 1. To determine compliance with Table 1, it would be necessary to model the induction process using the actual field values (direction, magnitude, and relative phase), and an appropriate physiological model (computational or physical), along with the orientation of the model with respect to the direction of the field.

For situations where there is a significant disparity in magnetic field exposure of the head and torso, the MPE flux density limits needed to meet the basic restrictions (Table 1) can change considerably. To illustrate this point, consider a 60 Hz field where only the torso is exposed versus one where both the head and torso are exposed. If only the torso were exposed, the MPE would be limited by peripheral nerve stimulation,

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rather than by brain synapse effects. For torso exposure, the MPE at 60 Hz would be 34.8 mT—roughly 13 times the limit of 2.71 mT for both head and torso exposure (Table 2).

The electric field reference levels in Table 4 are not based on the *in situ* electric field limits of Table 1; rather these limits are based on indirect electrostimulation. Spark discharge and contact currents will be acceptable if the average environmental electric field over the dimensions of the body does not exceed the Table 4 limits. These limits are based on the assumptions that the exposed person is insulated from ground, is much closer to the ground than the field source, and is within reach of a grounded conducting object.

6.11 Induced and contact current

6.11.1 General relationships

Strength-duration and strength-frequency curves characterize thresholds of nerve stimulation for contact currents. The rheobase threshold value of current into a contact electrode varies inversely with the contact area. A touch contact area of 1 cm^2 is assumed for the area of a light fingertip contact, whereas a much larger contact area (≅15 cm^2) can apply to a grasped contact. Consequently, separate values are cited in Table 5 for grip and touch contacts. The grasping contact limit in controlled environments pertains where personnel are trained to effect grasping contact and to avoid touch contacts with potentially energized conductors or grounded conductors when the person is the induction object. It is assumed that the general public is not aware of the possibility of conducted current from energized objects, and the method of contact is unconstrained. Specified limits reduce the probability that inadvertent contact with energized objects could lead to tiny localized burns of the outer layer of skin (with spark discharges), painful sensations, or startle reactions that, while not hazardous per se, could lead to an accident.

Numerous experiments with perception of sinusoidal current reveal a strength-frequency law with a minimum plateau below a critical frequency, f_e, above which thresholds converge to a frequency-proportional law when the current is of a continuous nature (Reilly [B75]). With continuous sinusoidal stimulation, frequency-proportional thresholds have been demonstrated in humans to a frequency of 100 kHz, above which thermal perception thresholds dominate (Chatterjee et al. [B23]; Dalziel and Mansfield [B27]). However, for pulsed sinusoidal waveforms, the frequency-proportional relationship can be extended into the MHz region as suggested by neurostimulation experiments in rats (LaCourse et al. [B55]), and in human experiments using brief (≅ 0.1 μs) pulses (Reilly [B75]).

Based on nerve excitation models, strength-duration and strength-frequency constants are connected by $f_e = 1/(2\tau_e)$. Consequently, factors leading to small values of τ_e would increase f_e. Experimental values of f_e vary significantly, although the factors accounting for this variation are not well understood. The Subcommittee has adopted the assumption that f_e for contact current is 3 kHz, allowing extrapolation to lower frequencies from thresholds determined at higher frequencies using a slope of f with a minimum threshold at and below 3 kHz. Further research will be needed to understand the variation of experimental constants observed in strength-duration and strength-frequency laws.

6.11.2 Illustration of statistical relationships

Pain levels with touch contact can be extrapolated from Chatterjee et al. [B23] to a frequency of 3.0 kHz, which is the postulated corner frequency (above which there is a frequency-proportional slope). At 10 kHz (the lowest frequency tested by Chatterjee), the mean pain level is 8.0 mA for adults (males and females mixed) and 6.0 mA for 10-year-old children. Those values may be converted to median thresholds by dividing by the factor 1.12 as noted in 6.8. The 10 kHz thresholds are extrapolated to a 3 kHz rheobase by applying the multiplier 0.3 (the ratio 3 kHz/10 kHz). The result is a median pain threshold of 2.14 mA for adults and 1.6 mA for 10-year-old children. Using a discomfort-to-pain ratio of 0.7 for contact current (see 6.2), the median discomfort rheobase level is estimated to be 1.5 mA for adults, and 1.12 mA for children. Applying these median values to the lognormal model with a median-to-one-percentile ratio of 3.0, the

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following reaction probabilities are determined. At a touch contact level of 0.5 mA (the MPE for the general public) in children: the probability of discomfort is 5%, and the probability of pain is 1%. In adults: the probability of discomfort is 1%, and the probability of pain is 0.1%. At a touch contact current level of 1.5 mA in adults: the probability of pain is 23%, and the probability of discomfort is 50%.

Current thresholds for perception and pain are considerably greater if contact is made with a grasping contact rather than a touch. A mean perception level for a grasping contact at 10 kHz is 13 mA for adults (Chatterjee et al. [B23]). Extrapolating to a frequency of 3 kHz, a median perception threshold of 3.48 mA is determined. The median discomfort or pain threshold is determined by applying the multipliers 2.4 and 1.7 respectively (see 6.2), resulting in a median rheobase discomfort level at 5.92 mA and a pain level at 8.35 mA. At a grasping contact current of 3 mA (specified in Table 5 for grasping contact MPE in controlled environments), the probability of discomfort in adults is estimated at 8%, and the probability of pain at 1.6%.

The contact current levels in Table 5 do not contain safety factors. The omission of safety factors is justified by noting that the reaction levels for contact current are better understood than are the other reaction thresholds addressed in this standard.

6.12 Medical devices and metallic implants

Medical devices and metallic implants may involve special health and safety problems when the individual using them is exposed to electric and magnetic fields. This standard does not necessarily provide protection against interference with such devices or hardware. The recipient or provider of these devices should be aware of the potential for hazards and precautions that may be necessary with such devices.

Electrically powered medical devices can be susceptible to interference from many different sources of electrical energy. Interference with medical devices can occur with exposures below those cited as thresholds for electrostimulation effects. While several types of medical devices have been designed for immunity to electrical interference (e.g., cardiac pacemakers), many devices in use have not been designed or tested for immunity. Even with reasonable immunity to interference, serious patient consequences may occur if the immunity is exceeded. The concerns for device interference extend over a broad range of electrically powered medical devices. Examples of such devices where there are concerns for interactions include, but are not limited to: pacemakers, defibrillators, drug delivery pumps, neurostimulators, hearing aids, apnea monitors, hospital beds, and powered wheelchairs. When deemed necessary, advice should be sought from the manufacturer of the device and/or from the patient's medical practitioner.

There are a few standards that address electromagnetic compatibility (EMC) of medical devices and the device performance during exposure. The most widely recognized medical device standard published by the International Electrotechnical Commission (IEC [B44]) covers many, but not all, medical devices. There are also general standards for active implantable medical devices that contain EMC requirements (ECES [B33]; IEC [B44]; ISO [B48]). In addition, work is underway to update the IEC medical equipment EMC standard and to develop more consistent standards for pacemakers and implantable defibrillators which include EMC requirements, such as in the United States (AAMI [B1]) and Europe (ECES [B34], [B35]).

Metallic implants comprise another class of medical implants, such as metallic stints, staples, and orthopedic rods and plates. In some cases, metallic implants may contact sensitive tissue, as with cardiac staples. Unlike the medical device, such implants may not have a failure mode due to electrical interference. Nevertheless, metallic hardware implanted in the body can enhance induced electric fields either by providing a magnetic induction loop, or a high conductivity region that can locally enhance the induced electric field, and thereby enhance the possibility of electrical stimulation in localized regions near the implant (Reilly and Diamant [B78]).

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Annex A

(informative)

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Annex B

(normative)

Magnetic induction model

The magnetic induction model used in developing this standard treats an exposed cross section of the body as an elliptical shape, with homogeneous conductivity. A solution for this model, applicable to situations where the wavelength of the field is much greater than body dimensions was published by Durney et al., [B32], and expressed in applied form by Spiegel [B93]. The present form used here is the one expressed by Reilly [B72]. A general expression for the induced E-field due to an incident B-field that is constant in magnitude and relative phase over the ellipse is shown in Equation (B.1)

$$E = -\dot{B}_w \left| \frac{a^2 u \boldsymbol{a}_v - b^2 v \boldsymbol{a}_u}{a^2 + b^2} \right| \tag{B.1}$$

where $\boldsymbol{a}_u$ and $\boldsymbol{a}_v$ 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 flux density in a direction perpendicular to the cross section. In the calculations that follow, the magnitude of the induced field, E, is expressed, rather than its vector components. 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.

Table B.1 summarizes the exposure conditions used to determine $\dot{B}_o$ data expressed in Table 7. The entries of Table B.1 are interpreted as follows. The second column expresses the exposure condition. For instance, the entry in the first row is interpreted as excitation of a 10 μm neuron located in the brain, with a magnetic field perpendicular to the sagittal cross section. The third column gives the semi-minor and semi-major axes of the ellipse. The fourth column gives the location within the cross section where the E-field is evaluated. The fifth column is the assumed rheobase value of E_o (from Table 6). The last column gives the values of $\dot{B}_o$ determined from Equation (B.1). In this formulation, it is assumed that an ellipse is fitted to the torso, body,

Table B.1—Elliptical exposure model used to compute magnetic induction[a, b]

Item	Exposure	b, a (cm, cm)	u, v (cm, cm)	E_o (V/m-pk)	$\dot{B}_o$ (T/s-pk)
1	10-μm nerve, brain, sagittal	9, 10.5	9, 0	12.3	237
2	Synapse, brain, sagittal	9, 10.5	9, 0	0.075	1.45
3	20-μm nerve, body, sagittal	17, 90	17, 0	6.15	37.5
4	20-μm nerve, torso, coronal	20, 40	20, 0	6.15	38.4
5	Heart, body, sagittal	17, 90	14, 18	12.0	88.7
6	Heart, torso, sagittal	17, 40	14, 18	12.0	98.6
7	Leg	9, 42	9, 0	6.15	71.5

[a] b,a represent semi-minor and semi-major axes, respectively, of ellipse fitted to particular body part, *viz:* the brain in items 1 and 2, the torso in item 4, and the whole body in items 3 and 5.

[b] (u,v) represents the location within the ellipse where the induced field was evaluated, where u and v are measured along the minor and major axes, respectively.

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or head in one of three orientations. Consequently, the reference system (*u, v*) is tied to the fitted ellipse and not to one specific reference system with respect to the body.

In items (1) and (2), the assumed ellipse is not supposed to represent the actual size of the brain, but rather the size of an ellipse that encloses its outer perimeter (the cerebral cortex) where the magnitude of the induced E-field is greatest. The ellipse enclosing the brain has semi-major and semi-minor axes that are 1.5 cm smaller than the assumed head size to account for the distance of 1.5 cm between the cortex and the scalp. Items (3) and (5) treat the exposure as uniformly covering the entire body; items (4) and (6) assume only the torso is exposed. The latter points are included to demonstrate that there is but a modest difference (about 10%) between worst-case exposure of the entire body versus exposure of only the torso with respect to peripheral nerve and cardiac stimulation.

The points *u,v* are selected to correspond to the worst-case exposure point for each of the assumed scenarios. In the case of the brain [items (1) and (2)], the cortex is where the induced E-field is greatest, and sagittal exposure provides the greatest magnetic induction loop. For items (3) and (5), an ellipse is fitted to the entire body viewed in the sagittal cross section. In the case of the heart, the point of greatest sensitivity to electrical stimulation is its apex (Roy et. al. [B84]), and the greatest induced field at that location is found with sagittal exposure (Reilly [B72]). The points (*u,v*) in items (5) and (6) correspond to the apex of the heart.

The exposure ellipses in Table B.1 correspond to a large (but not extreme) body size for adults based on anthropomorphic data (SAE [B85]). It is conservative to assume large body dimensions.

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