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Determining the peak spatial-average specific absorption rate (SAR) in the human body from wireless communications devices, 100 kHz to 10 GHz - Part 1: General requirements for using the finite-difference time-domain (FDTD) method for SAR calculations

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in the human body from wireless communications devices,
100 kHz to 10 GHz -
Part 1: General requirements for using the finite-difference
time-domain (FDTD) method for SAR calculations**

FOREWORD

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This document is published as an IEC/IEEE Dual Logo standard.

This second edition cancels and replaces the first edition published in 2017. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) specification of a SAR averaging algorithm for the calculation of the psSAR from computational results for arbitrarily shaped homogeneous phantoms, which avoids inconsistencies with respect to the algorithm for SAR averaging algorithm specified in IEC/IEEE 62209-1528 for SAR measurement methods;
- b) provision of SHA-256 checksums for all supplemental files;
- c) addition of brief informative discussion on developmental stages of IEC and IEEE computational modelling standards for SAR evaluations.

This standard contains attached files in the form of CAD models and reference results described in Annex B and Annex D. Download links and checksums for these files can be found in Annex E.

The text of this International Standard is based on the following IEC documents:

Draft	Report on voting
106/722/FDIS	106/733/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with the rules given in the ISO/IEC Directives, Part 2, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications/.

A list of all parts in the IEC/IEEE 62704 series, published under the general title *Determining the peak spatial-average specific absorption rate (SAR) in the human body from wireless communications devices, 100 kHz to 10 GHz*, can be found on the IEC website.

Future documents in this series will carry the new general title as cited above. Titles of existing documents in this series will be updated at the time of the next edition.

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- reconfirmed,
- withdrawn, or
- revised.

INTRODUCTION

Computational techniques have reached a level of maturity which allows their use in specific absorption rate (SAR) assessment of wireless communication devices. Some wireless communication devices are used in situations where SAR measurement is extremely complex or not possible at all. The benefits of consensus standards to users and regulators include standardized and accepted protocols, anatomically correct body models, verification and validation techniques, benchmark data, reporting format and means for estimating the computational uncertainty in order to produce valid, accurate, repeatable, and reproducible data.

Sample Document

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1 Scope

This part of IEC/IEEE 62704 defines the methodology for the application of the finite-difference time domain (FDTD) technique when used for determining the peak spatial-average specific absorption rate (psSAR) in the human body exposed to wireless communication devices with known uncertainty. It defines methods to validate the computational model of the device under test (DUT) and to assess its uncertainty when used in SAR simulations. Moreover, it defines procedures to determine the psSAR in a cubical volume and to verify the correct implementation of the FDTD simulation software. The applicable frequency range is 100 kHz to 10 GHz.

This document does not recommend specific SAR limits; these are found elsewhere, for example, in the guidelines published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [1]¹ or in IEEE Std C95.1 [2].

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC/IEEE 62209-1528:2020, *Measurement procedure for the assessment of specific absorption rate of human exposure to radio frequency fields from hand-held and body-mounted wireless communication devices - Human models, instrumentation, and procedures (Frequency range of 4 MHz to 10 GHz)*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

IEC, ISO and IEEE maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <https://www.electropedia.org/>
- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEEE Dictionary Online: available at <https://dictionary.ieee.org>

3.1

source

one or more edges of the mesh to which an associated signal feeds electric or magnetic energy

Note 1 to entry: The amplitude of the signal is proportional to an arbitrary function of time.

3.2

feed-point

<antenna> part of the radiating structure where the radio-frequency currents start to support the electromagnetic fields that carry energy away from the antenna

Note 1 to entry: Often the feed-point of the antenna is not accessible because of mechanical support requirements; in this case a connection point is available to inject radio-frequency energy into the antenna. Normally, the connection point is a simple connector or a waveguide flange. If not collocated, the connection and the feed-point of an antenna are interconnected by one or more sections of transmission line. By measuring the antenna impedance at the connection point, if the electrical characteristics of the transmission lines between the connection and the feed-point are known, it is possible to calculate the antenna feed-point impedance.

¹ Numbers in square brackets refer to the bibliography.

3.3**antenna feed-point impedance
terminal or driving-point impedance**

ratio of complex voltage to complex current at the terminals of a transmitting antenna, or the ratio of the open-circuit voltage to the short-circuit current at the terminals of a receiving antenna

3.4**background material**

material or tissue which is not considered for the averaging volume

Note 1 to entry: Most typically, a background material will be any lossless material, such as the free-space or air surrounding the anatomical model. It also includes air enclosures or other lumina inside the body and tissues that have been excluded from averaging, for example, by user selection.

3.5**benchmark**

simulation test specifically defined to verify simulation results based on comparison with a reference

3.6**body**

geometrical distribution of the dielectric properties and the mass densities of all live body tissues including body fluids

Note 1 to entry: The contents of body lumina or foreign matter, such as medical implants or jewellery, are not considered as part of the body.

3.7**conductivity**

σ

ratio of the magnitude of the conduction-current density in a medium to the electric field strength

Note 1 to entry: Conductivity is expressed in units of siemens per metre (S/m).

3.8**conservative exposure**

estimate of the peak spatial-average SAR and whole-body average SAR as defined in this document that is representative of what is expected to occur in the body of a significant majority of the population during normal operating conditions of wireless communication devices

[SOURCE: IEC/IEEE 62209-1528:2020, modified – In the definition, whole-body average SAR has been added and explicit mention of uncertainties has been deleted.]

3.9**coverage factor**

k

factor that is used to obtain the expanded uncertainty from the combined uncertainty with a known probability of containing the true value of the measurand

3.10**far-field**

region of the field of an antenna where the angular field distribution is essentially independent of the distance from the antenna

Note 1 to entry: In this region, the field has predominantly plane wave characteristics, i.e. the electric field strength and magnetic field strength distributions are locally uniform in planes transverse to the direction of propagation.

Note 2 to entry: For larger antennas especially, the far-field is also referred to as the Fraunhofer region.

3.11**mesh**

discrete representation of the simulation model as a set of voxels in a regular three-dimensional Cartesian arrangement

Note 1 to entry: In the scientific literature, the mesh is often referred to as "grid".

3.12**near-field**

region in the field of an antenna, located near the antenna, in which the electric and magnetic fields do not have substantial plane-wave characteristics, but vary considerably from point to point

Note 1 to entry: The term near-field is often vaguely defined and has different meanings for large and small antennas. The near-field is further subdivided into the reactive near-field, which is closest to the antenna and contains most or nearly all of the stored energy associated with the field of the antenna, and the radiating near-field. If the antenna has a maximum overall dimension that is not large compared to the wavelength, the radiating near-field possibly does not exist. For antennas large in terms of wavelength, the radiating near-field is sometimes referred to as the Fresnel region.

Note 2 to entry: For most antennas, the outer boundary of the reactive near-field is commonly taken to exist at a distance of $\lambda/2\pi$ from the antenna surface.

3.13**perfect electric conductor****PEC**

material with infinite electrical conductivity which does not dissipate any energy

3.14**relative permittivity**
 ϵ_r

ratio of the complex permittivity to the permittivity of free space

Note 1 to entry: The complex relative permittivity, $\epsilon_r = \epsilon/\epsilon_0$, of an isotropic, linear, lossy dielectric medium is from Formula (1)

$$\epsilon_r = \epsilon'_r - j\epsilon''_r = \epsilon'_r - j \frac{\sigma}{\omega\epsilon_0} = \epsilon'_r \left(1 - j \frac{\epsilon''_r}{\epsilon'_r} \right) = \epsilon'_r (1 - j \tan \delta) \quad (1)$$

where

ϵ_0 is the free space permittivity ($8,854 \times 10^{-12}$ F/m);

ϵ'_r is the relative permittivity or dielectric constant;

σ is the conductivity in siemens per metre (S/m);

$\tan \delta$ is the loss tangent.

Note 2 to entry: For the purposes of this document, the convention $e^{j\omega t}$ is used to describe time-varying electric fields.

3.15**permeability**
 μ

ratio of the magnetic flux density to the magnetic field strength at a point

Note 1 to entry: The permeability is expressed in units of henry per metre (H/m).

3.16**reactive field**

electric and magnetic fields surrounding an antenna or other electromagnetic devices that result in storage rather than propagation of electromagnetic energy

3.17**root-mean-square****RMS**

<of a periodic function> positive square root of the mean value of the square of the function taken over a given period

Note 1 to entry: For a periodic function y of t , the positive square root of y is from Formula (2):

$$Y_{\text{RMS}} = \left[\frac{1}{T} \int y(t)^2 dt \right]^{1/2} \quad (2)$$

where

Y_{RMS} is the RMS value of y ;

t is any value of time;

T is the period.

3.18**root-sum-square****RSS**

positive square root of the sum of the squares of the elements of a set of numbers

3.19**scattering**

process that causes waves incident on discontinuities or boundaries of media to be changed in direction, phase, or polarization

3.20**specific absorption rate****SAR**

time derivative (rate) of the incremental energy (dW) absorbed by (dissipated in) an incremental mass (dm) contained in a volume element (dV) of a given density (ρ)

$$SAR = \frac{d}{dt} \left(\frac{dW}{dm} \right) = \frac{d}{dt} \left(\frac{dW}{\rho dV} \right)$$

Note 1 to entry: SAR is expressed in units of watts per kilogram (W/kg) or equivalently milliwatts per gram (mW/g).

Note 2 to entry: SAR can be related to the electric field at a point by

$$SAR = \frac{\sigma |E|^2}{2\rho}$$

where

σ is the conductivity of the tissue in siemens per metre (S/m);

ρ is the mass density of the tissue in kilograms per cubic metre (kg/m³);

E is the peak electric field vector in volts per metre (V/m).

Note 3 to entry: SAR can be related to the increase in temperature at a point by

$$SAR \approx \frac{c\Delta T}{\Delta t} \bigg|_{t=0}$$

where

ΔT is the change in temperature in degree Celsius (°C);

Δt is the duration of exposure in seconds (s);

c is the specific heat capacity in joules per kilogram and degree Celsius (J/kg °C).

This assumes that measurements are made under "ideal" circumstances, i.e. no heat loss by thermal diffusion, heat radiation, or thermoregulation (blood flow, sweating, etc.). Moreover, this expression is valid only in the initial, linear regime of the temperature-time curve. If this linear regime does not exist, the provided expression is not used.

3.20.1

peak spatial-average specific absorption rate

psSAR

maximum average SAR within a local region based on a specific averaging volume or mass

Note 1 to entry: SAR is expressed in watts per kilogram (W/kg) or equivalently milliwatts per gram (mW/g).

Note 2 to entry: The specific averaging volume or mass can be, for example, any 1 g or 10 g of tissue in the shape of a cube.

Note 3 to entry: For the purpose of this document, when the averaging mass is not specified the peak spatial-average SAR refers to both 1 g and 10 g quantities. In several tables in this document, the peak spatial-average SAR for 1 g and 10 g is simply denoted as 1 g and 10 g SAR.

3.20.2

spatial-average specific absorption rate

sSAR

ratio of the total power dissipated in the averaging volume to the target mass of tissue within that volume

Note 1 to entry: SAR is expressed in watts per kilogram (W/kg) or equivalently milliwatts per gram (mW/g).

Note 2 to entry: The specific averaging volume or mass can be, for example, any 1 g or 10 g of tissue in the shape of a cube.

3.20.3

whole-body average specific absorption rate

quantity calculated as the power dissipated in the entire body divided by its mass

Note 1 to entry: SAR is expressed in watts per kilogram (W/kg) or equivalently milliwatts per gram (mW/g).

3.21

update coefficient

numerical value assigned to the voxel edges and faces calculated from the dielectric and magnetic properties of the voxels that surround it

Note 1 to entry: The update coefficient is used to advance the numerical values of the electric and magnetic fields in the mesh in time based on their present and past values.

3.22

voxel

volume element of the geometry to be discretized in the mesh

Note 1 to entry: In FDTD simulations for SAR calculation, the voxel is assigned the permittivity, permeability, the electric and magnetic conductivities and the mass density of the geometry. The electric-field components of the mesh are located in a tangential direction on the centres of the voxel edges, and the magnetic-field components of the mesh are located in a normal direction on the centres of the voxel faces. Each edge and face is assigned an update coefficient.

4 Abbreviated terms

ASCII	American Standard Code for Information Interchange
CFL	Courant–Friedrichs–Lewy
CT	computed tomography
DFT	discrete Fourier transformation
DUT	device under test
FDTD	finite-difference time-domain
FFT	fast Fourier transformation
FIT	finite integration technique
MIMO	multiple input multiple output
MRI	magnetic resonance imaging
PEC	perfect electric conductor
PMC	perfect magnetic conductor
PML	perfectly matched layers
psSAR	peak spatial-average specific absorption rate
RMS	root mean square
RSS	root sum square
SAM	specific anthropomorphic mannequin
SAR	specific absorption rate
sSAR	spatial-average specific absorption rate

5 Finite-difference time-domain method

5.1 Definition

This document applies the finite-difference time-domain (FDTD) method to calculate SAR. FDTD is extensively used for bio-electromagnetic calculations, dating back to 1975 for the analysis of microwave heating of a human eye (Taflov and Brodwin [3]). Initially, the user shall determine the applicability of this document by determining whether the specific computational solution of Maxwell's equations under consideration qualifies as an implementation of FDTD.

This is not entirely straightforward since there have been many variations of the FDTD method developed over the time since Kane Yee's original paper in 1966 [4], which may be taken as defining the fundamental FDTD method. Since then, the method has received significant attention in the scientific community. Numerous articles on the method and its extensions and applications have been published. Several textbooks on the FDTD method recapitulate its fundamentals, its further developments and its use ([5], [6]). Details on the application of the FDTD method are given in Annex C.

For the application of this document, the implementation of FDTD in the region where SAR is being calculated shall include the following characteristics.

- The electric field components are located on the edges of a Cartesian mesh composed of rectangular parallelepipeds.
- The magnetic field components are located on the edges of a Cartesian mesh composed of rectangular parallelepipeds which is offset from the electric field mesh by a half-voxel in each direction.

- The computational method is a finite-difference approximation of the Maxwell curl equations using central differences which are (at least globally) second-order accurate and may therefore include non-uniform meshes, which are also second-order accurate (Monk and Süli [7]).
- The computational method solves for both electric and magnetic fields by a fully explicit leapfrog time-stepping process.
- Gauss's laws are implicitly enforced, the fields are divergence-free, and charge is conserved.
- The time-stepping algorithm is non-dissipative. Thus, there is no spurious decay of energy due to non-physical artefacts of the algorithm, and artificial dissipation is not required for stability.

NOTE Complex numerical dispersion in non-uniform meshes leads to spurious rise or decay of field amplitudes [7]. For the applications of the scope of this document, these effects are generally negligible. The impact of the numerical dispersion is assessed within the uncertainty evaluation (Clause 7).

5.2 Requirements on the implementation of the FDTD method

The basic requirements on the FDTD method are given in Annex A. For compliance with this document, the FDTD method shall be implemented according to these requirements. The method shall be implemented in Cartesian coordinates in three spatial dimensions. Moreover, SAR calculation and averaging shall be implemented according to Clause 6. The implementation of the FDTD method shall be verified according to Clause 8.

Other methods or extensions, or both, of FDTD that satisfy the above definitions but provide additional features may be applied provided that these features have been fully verified according to the procedures in this document; code verification and benchmarks, etc. These alternative methods shall provide at least the same accuracy as the FDTD method defined above. The finite integration technique (FIT) in time domain can be regarded as an extension of FDTD in this context.

6 SAR calculation and averaging

6.1 General

Present RF exposure standards and guidelines specify time averaged whole-body average SAR limits and psSAR limits, neither of which shall be exceeded. The psSAR is usually averaged over a specified mass of tissue in a cubical volume, such as the trunk, the head, an extremity (e.g. limbs) or the pinnae. Averaging masses are specified in [1], [2] or other applicable guidelines.

The measurement standard that defines the SAM phantom and the testing positions is IEC/IEEE 62209-1528. The frequency range of IEC/IEEE 62209-1528 is from 4 MHz to 10 GHz, whereas the lower end of the frequency range of this document is 100 kHz. The assumptions on which the SAM phantom and the testing positions are based and which are outlined in IEC/IEEE 62209-1528 apply for SAR assessment regardless of the frequency limit. As the FDTD method does not have any intrinsic frequency limitations, the SAM phantom and the testing positions of IEC/IEEE 62209-1528 can be applied over the entire frequency range of this document.