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INTERNATIONAL STANDARD

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Determining the peak spatial-average specific absorption rate (SAR) in the human body from wireless communication devices, 30 MHz to 6 GHz – Part 4: General requirements for using the finite element method for SAR calculations

Détermination du débit d’absorption spécifique (DAS) maximal moyenné dans le corps humain, produit par les dispositifs de communications sans fil, 30 MHz à 6 GHz – Partie 4: Exigences générales d'utilisation de la méthode des éléments finis pour les calculs du DAS

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Part 4: General requirements for using the finite element method for SAR calculations

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

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

FDIS	Report on voting
106/515/FDIS	106/521/RVD

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

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

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, 30 MHz to 6 GHz*, can be found on the IEC website.

The IEC technical committee and IEEE technical committee have decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

Finite element methods have reached a level of maturity that allows their application in specific absorption rate (SAR) assessments of professional-use and consumer-use wireless communication devices. In the recent past, SAR compliance assessments for small transmitters were performed almost exclusively using measurements. Some wireless communication devices are used in situations where experimental SAR assessment is extremely complex or not possible at all. National regulatory bodies (e.g. US Federal Communications Commission) encourage the development of consensus standards and encouraged the establishment of the ICES Technical Committee 34 Subcommittee 2. The benefits to the users and the regulators include standardized and accepted protocols, verification and validation techniques, benchmark data, reporting format and means for estimating the overall assessment uncertainty in order to produce valid, repeatable, and reproducible data.

The purpose of this document is to specify numerical techniques and models to determine peak spatial-average specific absorption rates (SAR). SAR will be determined by applying finite element method simulations of the electromagnetic field conditions produced by wireless communication devices in models of the human anatomy. Intended users of this document are (but are not limited to) wireless communication device manufacturers, service providers for wireless communication that are required to certify that their products comply with the applicable SAR limits, and government agencies.

Several methods described in this document are based on techniques specified in IEC/IEEE 62704-1:2017.

DETERMINING THE PEAK SPATIAL-AVERAGE SPECIFIC ABSORPTION RATE (SAR) IN THE HUMAN BODY FROM WIRELESS COMMUNICATION DEVICES, 30 MHZ TO 6 GHZ –

Part 4: General requirements for using the finite element method for SAR calculations

1 Scope

This part of IEC/IEEE 62704 describes the concepts, techniques, and limitations of the finite element method (FEM) and specifies models and procedures for verification, validation and uncertainty assessment for the FEM when used for determining the peak spatial-average specific absorption rate (psSAR) in phantoms or anatomical models. It recommends and provides guidance on the modelling of wireless communication devices, and provides benchmark data for simulating the SAR in such phantoms or models.

This document does not recommend specific SAR limits because these are found elsewhere (e.g. in IEEE Std C95.1 [1][1] or in the guidelines published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [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 62209-1, *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 – Part 1: Devices used next to the ear (Frequency range of 300 MHz to 6 GHz)*

IEC/IEEE 62704-1:2017, *Determining the peak spatial-average specific absorption rate (SAR) in the human body from wireless communications devices, 30 MHz to 6 GHz – Part 1: General requirements for using the finite-difference time-domain (FDTD) method for SAR calculations*

IEEE Std 1528, *IEEE Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Head From Wireless Communications Devices: Measurement Techniques*

3 Terms and definitions

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

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

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

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1 Numbers in square brackets refer to the Bibliography.

3.1
mesh
<finite-difference time-domain method> 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 a "grid."

[SOURCE: IEC/IEEE 62704-1:2017, 3.21, modified – The specific context "<finite-difference time-domain method>" has been added.]

3.2
mesh
<finite element method> discrete representation of the simulation model as a set of tetrahedral elements in an irregularly three-dimensional arrangement

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

3.3
element
smallest three-dimensional part of a mesh

EXAMPLE A voxel or a tetrahedron.

3.4
subregion
spatially limited three-dimensional region within a computational domain

3.5
accepted power
power delivered to a load by a source

4 Abbreviated terms

ASCII	American Standard Code for Information Interchange
BVP	Boundary Value Problem
DoF	Degrees of Freedom
DUT	Device Under Test
FDTD	Finite-Difference Time-Domain
FEM	Finite Element Method
PDE	Partial Differential Equation
PEC	Perfect Electric Conductor
PMC	Perfect Magnetic Conductor
psSAR	peak spatial-average Specific Absorption Rate
SAR	Specific Absorption Rate
SI	International System of Units
TVFE	Tangential Vector Finite Elements

5 Finite element method – basic description

This document describes applications of the finite element method (FEM) to calculate the specific absorption rate (SAR). Reasons for using FEM include its proven track record in a broad range of electromagnetic applications, and its ability to use an unstructured, usually tetrahedral, mesh that conforms to complicated geometries, employing arbitrarily small elements where needed and larger elements elsewhere.

Multiple ways exist to solve Maxwell's equations with FEM. Implementations can be based on field quantities or on potential quantities, and may be formulated using either the weighted residual method or the variational method [3], [4]. The weighted residual method starts directly from the partial differential equation (PDE) of the boundary value problem, whereas the variational method starts from the variational representation of the boundary value problem. All implementations have the following in common:

a) They are based on PDEs, not on integral equations. The PDEs are derived from Maxwell's equations augmented by proper boundary conditions in order to frame a well-defined boundary value problem on a finite computational domain.

b) The size of the computational domain is finite. Radiation towards infinity is implemented through an open boundary condition on its outer boundaries. Radiated fields outside the domain can be computed by integrating over a boundary that encloses the radiating structure.

c) After applying excitations and boundary conditions and discretizing the computational domain into a mesh, the derived PDE is transformed into a matrix equation in which the matrix is large, sparse, and banded. "Large" is a consequence of having a large number of unknowns, several per element on a large mesh. "Sparse" and "banded" are consequences of the fact that all interactions are formulated as local interactions.

d) In the limit of infinitesimally small elements, the solution approaches the exact solution of the PDE.

Annex A contains more information on FEM, along with references to literature and a discussion of its limitations. Clause 8 describes a set of tests is described that shall be used to determine whether a particular implementation of FEM is correct and sufficiently accurate to be used for SAR calculations.

This document refers to Nédélec elements of the first kind, which are polynomially exact up to order 0 (H_0(curl) or edge elements) as lowest order; up to order 1 (H_1(curl) elements) as second lowest order; and up to order 2 (H_2(curl) elements) as third lowest order [5]. If an implementation of the FEM is applied with one of these orders, the respective parts of the code verification shall be executed with this order.

6 SAR calculation and averaging

6.1 General

The local specific absorption rate (SAR) in a location in tissue is given in Equation (1):

$$SAR = \frac{\sigma E^2}{2\rho} \tag{1}$$

where ρ is the mass density of the tissue, E is the magnitude of the electric field vector, and σ is the electric conductivity. Since the local SAR can vary strongly with position, the quantity of interest is often the peak spatial-average SAR. Contemporary safety standards and guidelines specify time-averaged whole-body-averaged SAR limits and psSAR limits, neither of which should be exceeded. The spatial-average SAR is averaged over a specified mass with a specified volume, e.g. 1 g or 10 g of tissue in the shape of a cube [1], [2].

NOTE Cubical averaging volumes are applied in all existing standards for the measurement of psSAR, and are also recommended by [1], [2] and [6]. Other averaging volumes have been proposed, e.g. in [2], and might be included in future revisions of this document.

6.2 SAR averaging

6.2.1 General

The objective of the methods to evaluate the psSAR described here is to yield results that correspond to the methods and definitions of Clause 6 of IEC/IEEE 62704-1:2017, which describes how to compute psSAR on a rectangular mesh. The same algorithm shall be applied to calculate psSAR for FEM simulations within this document. Since the algorithm of Clause 6 of IEC/IEEE 62704-1:2017 is specified on rectilinear meshes with varying mesh step, the vector components of the electric fields, the conductivity, and the mass density of the finite element mesh shall be resampled on a Cartesian mesh. The resampling is carried out with increasingly fine mesh steps until convergence of the dissipated power is reached in the subregions where local SAR maxima are located. In order to reduce the computation time for the iterative resampling and SAR averaging, subregions with local SAR maxima are identified in a pre-scan. In these subregions, the psSAR is then calculated according to Clause 6 of IEC/IEEE 62704-1:2017. The maximum psSAR of all subregions shall be reported as the psSAR maximum together with its interpolation uncertainty. The details of the steps of the algorithm are provided in 6.2.2.

6.2.2 Evaluation of psSAR with an FEM mesh

6.2.2.1 General

The following steps shall be carried out to resample the geometry and the power density in a set of subregions around local SAR maxima for the application of the SAR averaging algorithm of IEC/IEEE 62704-1:2017.

a) Specify an orientation of a rectilinear mesh relative to the coordinate system of the FEM mesh considering the relevant features of the model; this orientation shall align with surface planes or conducting planes of the phantom or of the DUT.

b) Iteratively resample the geometry and local SAR distribution in the rectilinear mesh and evaluate psSAR at each iteration until convergence is achieved (see 6.2.2.2).

c) Report the highest psSAR of all subregions together with its interpolation uncertainty.

6.2.2.2 Calculation of the psSAR on an iteratively refined rectangular mesh

The psSAR shall be evaluated on a rectilinear mesh that encompasses a subregion around a local SAR maximum with individual equidistant mesh steps for each axis. Each mesh cell is assigned the local distribution of the dissipated power, the conductivity, and the mass density.

a) The mass density for each mesh cell shall be assigned by nearest-neighbour interpolation of the mass density distribution of the tetrahedral mesh.

b) The conductivity for each mesh cell shall be assigned by nearest-neighbour interpolation of the mass density distribution of the tetrahedral mesh.

c) In the mesh cells that have a mass density different from zero, the dissipated power density is calculated by evaluating the electric field of the finite element mesh in the centre of the mesh cell of the rectilinear mesh.

d) The initial mesh step length Δ_0 for each axis of the rectilinear mesh shall be calculated in accordance with Equation (2):

$$\Delta_0 \leq \sqrt[3]{\frac{m}{\rho_{\text{max}}}} \tag{2}$$

where

m is the averaging mass of the target volume;

ρ_{max} is the maximum mass density of the geometry in the computational domain.

e) The psSAR for the subregion under evaluation shall be calculated on the initial mesh according to the procedure specified in IEC/IEEE 62704-1:2017. Then the subregion shall be resampled on a rectilinear mesh with a reduced mesh step size $\Delta_{i+1} = 0{,}5\ \Delta_i$. This procedure shall be repeated until the difference in psSAR from the previous iteration to the present iteration is less than 1 %.

6.3 Power scaling

In FEM simulations, the accepted power is generally delivered to the device by means of a port with known characteristic impedance. Depending on the input impedance of the device, a specific power level is accepted by the antenna or load. The simulation results, including SAR, will be relative to this accepted power. To obtain the SAR for a different accepted power level, such as the target accepted power, the SAR results shall be adjusted by scaling using Equation (3):

$$SAR_{\text{scaled}} = SAR_{\text{scaled}} \frac{P_{\text{acc,target}}}{P_{\text{acc,computed}}} \tag{3}$$

where

$P_{\text{acc,target}}$ is the target accepted power;

$P_{\text{acc,computed}}$ is the accepted power computed by the FEM simulation.

For these calculations, $P_{\text{acc,computed}}$ is the power delivered to the load by the simulation, which is found from the complex voltage and current at the feed-point of the FEM mesh in accordance with Equation (4):

$$P_{\text{acc,computed}} = \frac{1}{2}\text{Re}\left\{UI^*\right\} \tag{4}$$

where U and I are complex quantities, and the asterisk indicates complex conjugate.

If an incident plane wave source is applied, SAR can be scaled based on the incident power density. The incident power density can be computed using Equation (5):

$$P_{\text{inc}} = \frac{1}{2}\text{Re}\left\{E_{\text{inc}} \times H_{\text{inc}}^*\right\} \tag{5}$$

where E_{inc} and H_{inc} represent the incident electric field and magnetic field from the plane wave. The computed incident power density can then be used to scale the SAR in the same manner as the accepted power.

Changes in SAR due to performance variations in radio frequency (RF) components that affect $P_{\text{acc,target}}$ (due to thermal, electrical, or other tolerances) shall be determined during experimental validation of the numerical model of the DUT (see 7.3). It shall be considered either by choosing the maximum possible value for $P_{\text{acc,target}}$ or by adding the performance variation in the uncertainty budget (see 7.4).

7 Considerations for the uncertainty evaluation

7.1 General

Assuming the FEM code has been implemented correctly, which shall be determined with the tests described in Clause 8, some uncertainties remain. This Clause 7 shows how they shall be evaluated to obtain a measure of overall assessment uncertainty. It follows the computational uncertainty scheme of Clause 7 in IEC/IEEE 62704-1:2017, with modifications appropriate to FEM. As stated in the cited clause, the computational uncertainties are divided into the following three categories:

a) discretization accuracy and uncertainty due to mesh density,

b) numerical accuracy of the specific FEM implementation,

c) accuracy of the numerical representation of the actual DUT.

Subclauses 7.2 through 7.4 specify general procedures for the evaluation of the uncertainty. When applied to device or application-specific FEM-based SAR simulation standards, there might be modifications appropriate to those applications. Further information can be found in Clause 7 of IEC/IEEE 62704-1:2017 and in [7], [8].

7.2 Uncertainty due to device positioning, mesh density, and simulation parameters

7.2.1 General

A representative model of the test configuration shall be used to determine the uncertainties due to mesh density, open boundary conditions, and other associated simulation parameters. For FEM, the contributions to the uncertainty due to device and phantom positioning are considered small because the mesh adapts to the surface of arbitrarily shaped objects. The remaining uncertainties are assumed to be covered in the evaluation of the uncertainty of the mesh density. Table 1 shows an example template for the quantification of the numerical uncertainty due to contributions described in 7.2.2 through 7.2.6.

Table 1 – Budget of the uncertainty contributions of the numerical algorithm and of the rendering of the test-setup or simulation-setup

a	b	c	d	e	f	g	h
Uncertainty component	**Subclause**	**Tolerance (%)**	**Probability distribution**	**Divisor $f(d, h)$**	c_i	**Uncertainty (%)**	v_i **or** v_{eff}
Mesh convergence	7.2.2		N	1	1		
Open boundary conditions	7.2.3		N	1	1		
Power budget	7.2.4		N	1	1		
Convergence of psSAR sampling	7.2.5		R	1,73	1		
Phantom dielectrics	7.2.6		R	1,73	1		
Combined std. uncertainty (k = 1)							

NOTE 1 Column headings a to h are given for reference.

NOTE 2 Columns c, g, and h are filled in based on the results of the DUT simulations.

NOTE 3 Abbreviations used in Table 1:

N, R, U – normal, rectangular, U-shaped probability distributions

Divisor – divisor used to get standard uncertainty

NOTE 4 The divisor is a function of the probability distribution and degrees of freedom (v_i and v_{eff}).

NOTE 5 c_i is the sensitivity coefficient that is applied to convert the variability of the uncertainty component into a variability of psSAR.