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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

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National foreword

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INTERNATIONAL STANDARD

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

INTERNATIONAL
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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

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

This standard contains attached files in the form of CAD models and reference results described in Annexes B and D. These files are available at: http://www.iec.ch/dyn/www/f?p=103:227:0::::FSP_ORG_ID,FSP_LANG_ID:1303,25.

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FDIS	Report on voting
106/401A/FDIS	106/413/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.

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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.

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- withdrawn,
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1 A list of IEEE participants can be found at the following URL: http://standards.ieee.org/downloads/62704/62704-1-2017/62704-1-2017_wg-participants.pdf.

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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 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, anatomically correct body models, validation techniques, benchmark data, reporting format and means for estimating the computational uncertainty in order to produce valid, accurate, repeatable, and reproducible data.

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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

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 (SAR) in the human body exposed to wireless communication devices with known uncertainty. It defines methods to validate the numerical model of the device under test (DUT) and to assess its uncertainty when used in SAR simulations. Moreover, it defines procedures to determine the peak spatial-average SAR in a cubical volume and to validate the correct implementation of the FDTD simulation software. The applicable frequency range is 30 MHz to 6 GHz.

NOTE Cubical averaging volumes are applied in all current experimental standards for the assessment of the peak spatial-average SAR (psSAR) and recommended by [1], [2] and [3]. Other averaging volumes have been proposed, for example, in [1], and may be included in future revisions of this document.

This document does not recommend specific SAR limits since these are found elsewhere, for example, in the guidelines published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [1] or in IEEE Std C95.1 [3].

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.

NOTE The experimental standards that define the SAM phantom and the testing positions are IEEE Std 1528 and IEC 62209-1.

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*

IEC 62209-1, *Human Exposure to Radio Frequency Fields from Hand Held and Body Mounted Wireless Communication Devices – Human Models, Instrumentation and Procedures – Part 1: Procedure to determine the specific absorption rate (SAR) for devices used next to the ear (frequency range of 300 MHz to 6 GHz)*

IEC 60050 (all parts), *International Electrotechnical Vocabulary (IEV)* (available at: http://www.electropedia.org)

IEEE Standards Dictionary Online (subscription available at: http://dictionary.ieee.org)

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3 Terms and definitions

For the purposes of this document, the terms and definitions given in the IEEE Standards Dictionary Online, IEC 60050 (all parts) and the following 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

3.1
excitation source
source with an associated signal which feeds electric or magnetic energy to one or more edges of the mesh

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

3.1.1
added source
source whose amplitude is added to the present value of an E-field component on a mesh edge at each time step of the FDTD algorithm

3.1.2
hard source
source whose amplitude replaces the present value of an E-field component on a mesh edge at each time step of the FDTD algorithm

3.1.3
voltage source
source whose amplitude updates the present value of an E-field component on a mesh edge at each time step of the FDTD algorithm considering the current through the mesh edge represented by its surrounding H-fields and an internal resistance

3.2
antenna
part of a transmitting or receiving system that is designed to radiate or to receive electromagnetic waves

3.3
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 driving point or feed-point impedance of an antenna.

3.4
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

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3.5
attenuation
decrease in magnitude of a field quantity in the transmission from one point to another

Note 1 to entry: Attenuation is expressed as a ratio.

3.6
average power
$\overline{P}$
time-averaged rate of energy transfer

$$\overline{P} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} P(t)\,\mathrm{d}t \tag{1}$$

where $P(t)$ is the instantaneous power

Note 1 to entry: The time duration could be source related (for example, the source repetition period, duty cycle) or use related.

3.7
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.

3.8
benchmark simulation
simulation test specifically defined to validate simulation results based on comparison with a reference

3.9
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.

3.10
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).

3.11
conservative estimate
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 population during normal operating conditions of wireless communication devices

Note 1 to entry: Conservative estimate does not mean the absolute maximum SAR value that could possibly occur under every conceivable combination in the human body size, shape separation from the antenna and/or vehicle.

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3.12
coverage factor
k
factor that is used to obtain the expanded uncertainty from the combined uncertainty with a known probability (P) of containing the true value of the measurand

Note 1 to entry: Specifically, k × (combined uncertainty) = (expanded uncertainty). When $k = 1$, $P \approx 0{,}68$; $k = 2$, $P \approx 0{,}95$; $k = 3$, $P \sim 0{,}999$.

3.13
electric field
E-field
vector field of electric field strength

3.14
electric field strength
E
at a given point, the magnitude (modulus) of the vector limit of the quotient of the force that a small stationary charge at that point will experience, by virtue of its charge, to the charge as the charge approaches zero in a macroscopic sense

Note 1 to entry: This may be measured either in newtons per coulomb or in volts per metre. This term is sometimes called the E-field intensity, but such use of the word intensity is deprecated, since intensity connotes power in optics and radiation.

3.14.1
electric field strength
<signal-transmission system> magnitude of the potential gradient in an E-field expressed in units of potential difference per unit length in the direction of the gradient

3.14.2
electric field strength
<radio wave propagation> magnitude of the E-field vector

Note 1 to entry: The electric field strength is expressed in volts per metre (V/m)

3.15
electrical length
length of a transmission medium or a transmission line, such as an antenna or a waveguide in any medium including air

Note 1 to entry: Electrical length is expressed in wavelengths, radians, or degrees. When expressed in angular units, it is a distance in wavelengths multiplied by 2π to yield radians, or by 360 to yield degrees.

3.16
electromagnetic field
EM field
electromagnetic phenomenon expressed in scalar or vector functions of space and time, for example, a time-varying field associated with electric and magnetic forces and described by Maxwell's equations

3.17
far-field region
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 (also called the free-space 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 region is also referred to as the Fraunhofer region.

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3.18
incident wave
wave, travelling through a medium, in a specific direction, which impinges on a discontinuity or a medium of different propagation characteristics

3.19
magnetic field
H-field
vector field of magnetic field strength

3.20
magnetic field strength
H
magnitude of the magnetic field vector

Note 1 to entry: The magnetic field strength is expressed in amperes per metre (A/m).

Note 2 to entry: For time harmonic fields in a medium with linear and isotropic magnetic properties, H is equal to the ratio of the magnetic flux density B to the magnetic permeability of the medium μ, i.e., $H = B/\mu$.

3.21
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”.

3.22
near-field region
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 region is often vaguely defined and has different meanings for large and small antennas. The near-field region is further subdivided into the reactive near-field region, 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 region. If the antenna has a maximum overall dimension that is not large compared to the wavelength, the radiating near-field region may not exist. For antennas large in terms of wavelength, the radiating near-field region is sometimes referred to as the Fresnel region.

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

3.23
perfect electric conductor
PEC
material with infinite electrical conductivity which does not dissipate any energy

3.24
relative permittivity
ε_r
ratio of the complex permittivity to the permittivity of free space

Note 1 to entry: The complex relative permittivity, $\varepsilon_r = \varepsilon/\varepsilon_o$, of an isotropic, linear, lossy dielectric medium is given by $\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' = \varepsilon_r' - j\dfrac{\sigma}{\omega\varepsilon_0} = \varepsilon_r'\left(1 - j\dfrac{\varepsilon_r''}{\varepsilon_r'}\right) = \varepsilon_r'(1 - j\tan\delta)$

where

ε_0	is the free space permittivity (8,854 × 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.

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

Note 3 to entry: The permittivity of biological tissues is frequency dependent and may be a complex tensor quantity.

3.25
penetration depth
for a given frequency, the depth at which the electric field (E-field) strength of an incident plane wave, penetrating into a lossy medium, is reduced to $1/e$ of its value just beneath the surface of the lossy medium

Note 1 to entry: For a plane-wave incident normally on a planar half-space, the penetration depth δ is given in Formula (2):

$$\delta = \frac{1}{\omega}\left[\frac{\mu_0 \varepsilon'_r \varepsilon_0}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega \varepsilon'_r \varepsilon_0}\right)^2}-1\right)\right]^{-1/2} \tag{2}$$

3.26
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).

3.27
reactive field
electric and magnetic fields surrounding an antenna or other electromagnetic devices that result in storage rather than propagation of electromagnetic energy

3.28
root-mean-square value
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

$$Y_{\text{rms}} = \left[\frac{1}{T}\int y(t)^2\,dt\right]^{1/2} \tag{3}$$

where

Y_{rms} is the rms value of y;

t is any value of time;

T is the period.

3.29
root-sum-square value
rss
positive square root of the sum of the squares of the elements of a set of numbers

3.30
scattering
process that causes waves incident on discontinuities or boundaries of media to be changed in direction, phase, or polarization

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3.31
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):

$$SAR = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}W}{\mathrm{d}m}\right) = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}W}{\rho\,\mathrm{d}V}\right) \tag{4}$$

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 E-field at a point by

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

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/m^3);

$\boldsymbol{E}$ 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

$$SAR \approx \left.\frac{c\Delta T}{\Delta t}\right|_{t=0}$$

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.

3.31.1
peak spatial-average specific absorption rate
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.

3.31.2
spatial-average specific absorption rate
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.

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3.32
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).

3.33
steady-state feed-point current
electric current flowing through the antenna feed-point in the steady-state regime of harmonic excitation at the operating frequency

3.34
steady-state feed-point voltage
voltage established at the antenna feed-point in the steady-state regime of harmonic excitation at the operating frequency

3.35
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.

3.36
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 E-field components of the mesh are located in a tangential direction on the centres of the voxel edges, and the H-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

ABC	Absorbing Boundary Condition
ASCII	American Standard Code for Information Interchange
CFL	Courant Friedrich 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
SAR	Specific Absorption Rate

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5 Finite-difference time-domain method – basic 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 (Taflove and Brodwin [4]). In order to determine applicability of this document, it shall be clear whether a specific numerical solution of Maxwell's equations 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 [5], 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 text books on the FDTD method recapitulate its fundamentals, its further developments and its use ([6], [7], [8]). Details on the application of the FDTD method are given in Annex C.

This document is based in part on the extensive validation of FDTD as it applies to SAR calculation reported in the literature. Therefore, for the application of this document, the implementation of FDTD in the spatial region where SAR is being calculated shall include the following characteristics.

- The electric field components are spatially located on the edges of a Cartesian coordinate system structured mesh composed of rectangular parallelepipeds.
- The magnetic field components are spatially located on the edges of a Cartesian coordinate system structured mesh composed of rectangular parallelepipeds which is offset from the electric field mesh by a half-voxel in each direction.
- The numerical solution method is a finite-difference approximation of the Maxwell curl equations using central differences which are (at least globally) second-order accurate and would therefore include non-uniform meshes, which are also second-order accurate (Monk and Süli [9]).
- The numerical solution 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 [9]. 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).

Artificial dissipation may be introduced in certain finite-difference algorithms in order to prevent or limit the spurious generation of energy in the computational domain which can lead to numerical instabilities. Such artificial dispersion is not required for the FDTD algorithm as defined here.

The basic requirements on the FDTD method are given in Annex A. Other methods and/or extensions of FDTD that satisfy the above definitions but provide additional features may be applied provided that they have been fully validated according to the procedures in this document; code validation and benchmarks, etc. However, 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.

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6 SAR calculation and averaging

6.1 Calculation of SAR in FDTD voxels

Since the electric fields in the FDTD mesh are located on the voxel edges, the x-, y-, and z-directed power components associated with a voxel are defined in different spatial locations. For SAR calculations, these components shall be summed with a defined mathematical procedure (see below).

The 12-field-components approach correctly interpolates all components in the centre of the voxel (using linear interpolation), defining the power dissipation at the voxel centre for which tissue density and conductivity can be unambiguously specified (D.1). Since all the field components used in the interpolation are tangential components of the voxel faces, the constitutive relations hold even if the voxel is located at interfaces of different materials or tissue types. The numerical accuracy of the interpolation with respect to the SAR calculation is discussed in [11]. This approach does not compromise the accuracy of the computed results since the order of accuracy of the interpolations involved is the same as that of the underlying FDTD data.

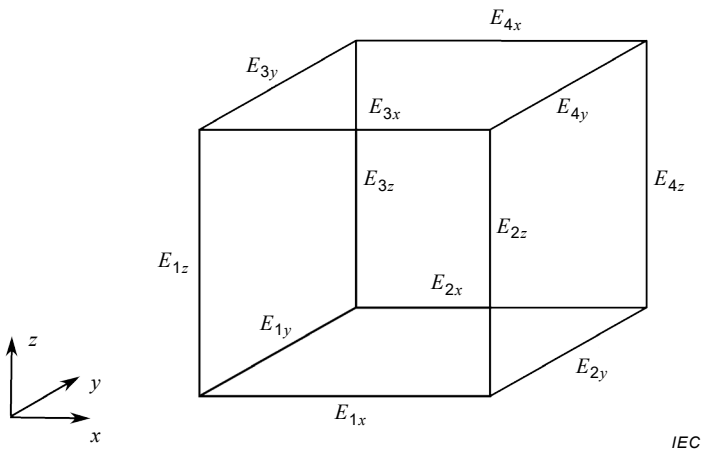

Figure 1 – Field components on voxel edges

To compute the SAR for a single FDTD voxel using the 12-field-components approach, the complex vector components of the complex amplitude of the E-field at each individual voxel edge shall be averaged into the voxel centre using linear interpolation:

$$E_x = \frac{1}{4}\left(E_{1x} + E_{2x} + E_{3x} + E_{4x}\right) \tag{5}$$

$$E_y = \frac{1}{4}\left(E_{1y} + E_{2y} + E_{3y} + E_{4y}\right) \tag{6}$$

$$E_z = \frac{1}{4}\left(E_{1z} + E_{2z} + E_{3z} + E_{4z}\right) \tag{7}$$

The locations of the electric field components on the voxel edges are shown in Figure 1. The SAR is then calculated using the conductivity σ_{voxel} and mass density ρ_{voxel} assigned to the respective voxel (Annex A).

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$$SAR = \sigma_{\text{voxel}} \frac{|E_x|^2 + |E_y|^2 + |E_z|^2}{2\rho_{\text{voxel}}} \tag{8}$$

In this manner, the unique conductivity and material density which have been assigned to the voxel in the FDTD mesh are preserved. Since only the tangential components of the voxel are used in the interpolation, the material properties of the adjacent voxels or the update coefficients of the respective edges need not be regarded. The factor of 2 in the denominator of Formula (8) takes into account the use of the magnitudes of the complex E-field amplitudes.

6.2 SAR averaging

6.2.1 General

Present RF exposure standards and guidelines specify time averaged whole-body-averaged SAR limits and peak spatial-average SAR limits, neither of which shall be exceeded. The peak spatial-average SAR 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. Different averaging masses may apply for body tissue and extremity tissue [1], [3]. When averaging SAR over tissue in the body, or over an extremity, only SAR values from tissues or extremities requiring the same averaging volume or mass and SAR limit shall be considered in the averaging. If any cubic volume contains tissue from the body and from an extremity, each shall be considered separately. Specifically, when determining the peak spatial-average SAR in a cube of tissue in the body, any tissue belonging to an extremity that may be contained in the cube shall be disregarded. Similarly, when determining the peak spatial-average SAR in tissues in an extremity, any tissue contained in the cube from the body shall also be treated as background material. The orientations of the cubes used for SAR averaging shall align with the coordinate axes used in the numerical computational procedures.

The regions of tissue that shall be considered as an extremity are defined by the applied RF exposure standard. The averaging algorithm follows the same definition for body tissues and extremities. The SAR averaging software shall provide appropriate means for the selection of the extremity tissues and body regions.

A procedure for the calculation of the peak spatial-average SAR is given in Annex E of [12]. However, it contains some ambiguities and open issues which can lead to inconsistent results in different implementations of the algorithm. In order to obtain consistent results in numerical SAR evaluation with different simulation tools, this document reformulates the procedure set forth in Annex E of [12]. This procedure is taken as the basis, to which minor modifications and additions are made in this document in order to address the ambiguities of flagging the states of the voxels (Table 1) and clearly define their contribution to the averaging volume. These modifications and additions are as follows.

- A definition on how to flag partially used voxels, i.e. voxels which are intersected by one or more faces of the averaging cube. These voxels shall not be flagged as “used”. The procedure in [12] was not specific in this case.
- An additional criterion for averaging around unused voxels, in the rare case that the procedure results in more than one possible averaging cube.
- A new rule that limits the maximum amount of background material (3.7) in an averaging cube. This will be limited to 10 % of background material by volume. This means that the cubical volume which is averaged about a valid voxel and consists of valid and/or used voxels shall not contain more than 10 % of background material. The mass of the background material does not contribute to the target mass.
- All faces of the cubical volumes of the valid voxels shall intersect the tissue or be entirely embedded in it. A tangential face on an interface of tissue and background material is regarded as entirely embedded in the tissue. The fraction of the background material shall be determined after the volume has reached the target mass.

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- For tissue in the body, the spatial-average SAR shall be evaluated in cubical volumes that contain a mass that is within a tolerance limit of ±0,000 1 % of the target mass.

Figure 2 shows a flow chart with the most relevant steps of the algorithm. 6.2.2 defines its implementation in detail.

NOTE Interlaboratory comparison studies conducted with different implementations of the algorithm for the calculation of the peak spatial-average SAR (psSAR) have shown that a tolerance of ±0,000 1 % for the averaging mass is required to achieve consistent averaging statuses of the voxels of the SAR Star benchmark (8.2.4). While the tolerance may appear unnecessarily low, it does not represent a technical problem with respect to the implementation and does not lead to convergence problems when applying the algorithm in practical situations.

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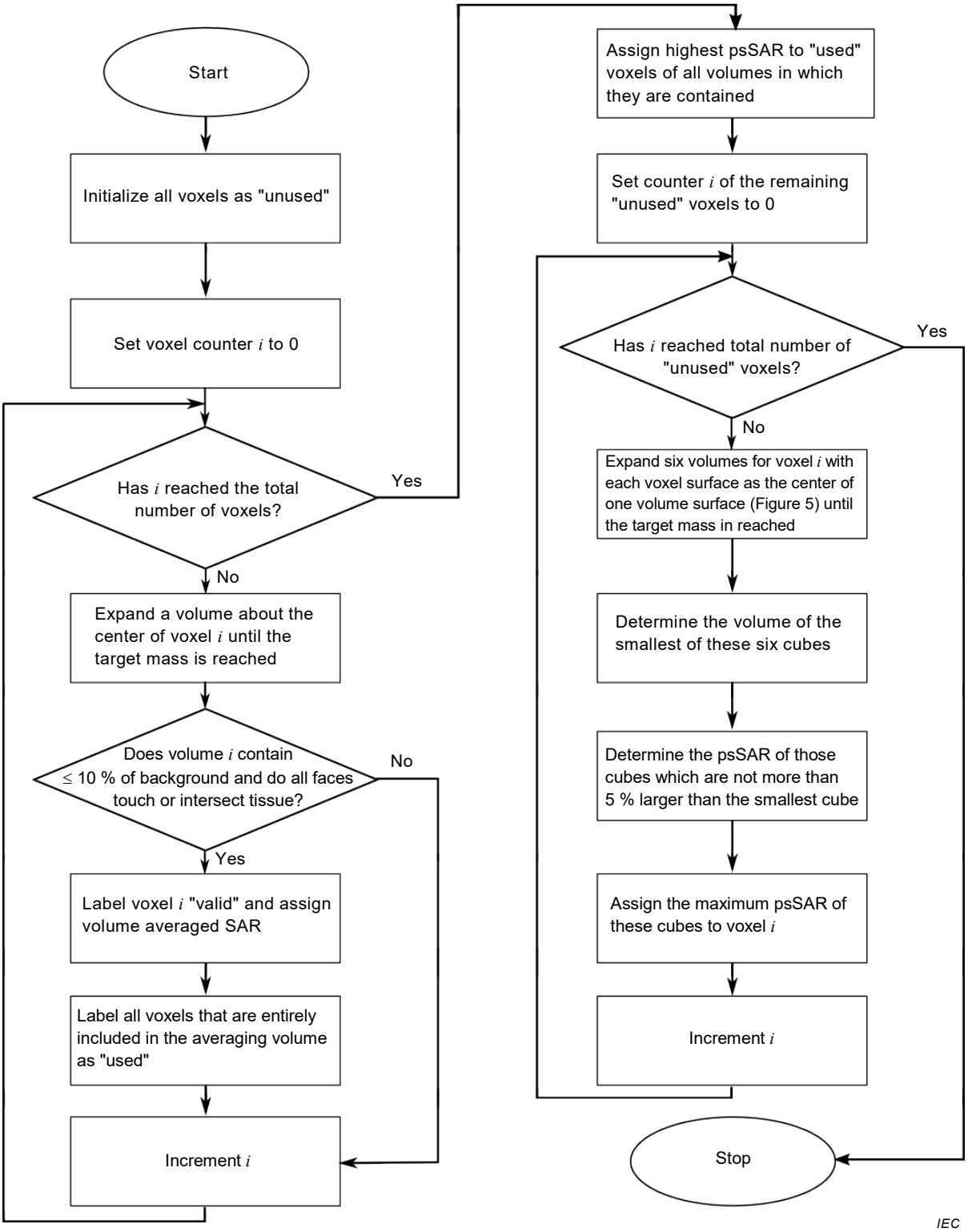

Figure 2 – Flow chart of the SAR averaging algorithm

6.2.2 Calculation of the peak spatial-average SAR

In order to determine the peak spatial-average SAR, a spatial-average SAR value is calculated for each voxel. All voxels shall be initialized with the label “unused”. In a first step, the averaging algorithm shall step through all the voxels in the body. The cubical volume centred at each voxel location, as defined above, shall be expanded evenly in all orientations ($\pm x$, $\pm y$ and $\pm z$) until the desired value for the target mass is reached. When expanding the

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volume, the outermost layer of the averaging cube may require partial voxels to be considered, in order to achieve the required target mass. As a consequence, the outermost layer of voxels in an averaging cube may contain partially included voxels to achieve the required averaging mass. If the resulting cube contains less than or equal to 10 % of background material by volume (Figure 3) and all of its faces touch (for entirely contained voxels) or intersect (for partially contained voxels) the tissue, then its centre voxel shall be labelled as "valid". Otherwise, the averaging cube shall not be used to compute spatial-average SAR. During this process, reference shall be kept of all voxel locations that have entirely been included (flagged as “used”) in an averaging cube to compute the spatial-average SAR. A voxel is regarded as entirely included in the averaging volume if 99,9 % of its volume is encompassed by the cube. Spatial-average SAR values are assigned to the centre voxel location of each valid averaging cube. All voxels which are included entirely in an averaging cube shall be labelled as "used" to indicate that they have been part of at least one averaging volume. While voxels which are included partly in an averaging cube do have a partial contribution to the SAR calculation, they are not labelled as “used”. The contribution of these voxels to the spatial-average SAR shall be calculated using linear interpolation of the absorbed power, considering the fraction of their volume encompassed by the averaging volume. At the end of this first step, the voxels deep inside the body will typically be centres of valid averaging cubes, while many of the voxels near the surface will have been labelled as “used,” although no spatial-average SAR has been determined for them yet (Figure 4). Those voxels which form curved or uneven surfaces or thin parts of the body may not be included in any valid averaging volume and may therefore keep their “unused” label.

The locations that are labelled as “used” and have never been in the centre of an averaging cube shall be assigned the largest spatial-average SAR value of the averaging cubes in which they are enclosed.

For all “unused” voxel locations, new averaging cubes shall be constructed in a second step by expanding the averaging cube with individual surfaces of the “unused” voxel centred on a surface of the averaging cube. For each “unused” voxel, six averaging cubes shall be determined, each of which has the “unused” voxel centred on its surface. The other five faces of the cube shall be expanded evenly in their normal orientations until the target mass of tissue in the body is enclosed within the volume of the cube regardless of the amount of enclosed background material (Figure 5). The spatial-average SAR values of those cubes whose volume is not larger than 5 % of the volume of the smallest cube shall be preselected. The highest spatial-average SAR value of these preselected cubes shall be assigned to the “unused” voxel.

NOTE As the objective of the algorithm is to find the cube with the smallest percentage of background material for a given mass, a tolerance of 5 % on the cube size is introduced because numerical uncertainties in the calculation of the power absorbed in the voxels can lead to ambiguities in cases where more than one cube of approximately the same volume can be grown. Intercomparison studies with different implementations have shown that a tolerance of 5 % on the volume reliably identifies the maximum peak spatial-average SAR in such situations.

If the entire mass of the tissues to be averaged is less than the target mass, the peak spatial-average SAR shall be determined as the ratio of the total power dissipated in the tissues to be averaged to the entire mass of these tissues. For example, this situation can occur when averaging over the pinna of an anatomical model of a child excluding the head tissue and using an averaging cube of 10 g. The tissue masses of children’s pinnae are typically below 10 g.

When implementing the algorithm, growth of the averaging volumes beyond the boundaries of the computational domain shall be avoided as this may lead to an undefined state of the algorithm.

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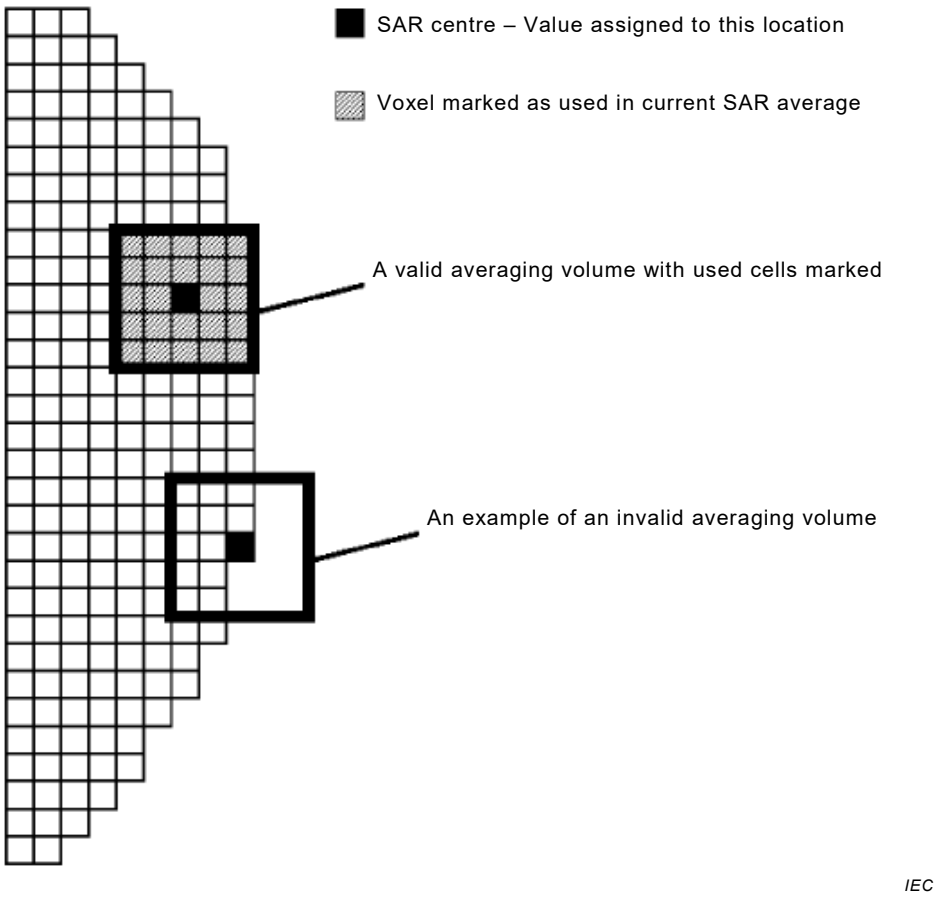
Table 1 – Voxel states during SAR averaging

Voxel label	Definition
unused	initial state of all voxels upon initialization of the averaging algorithm (The voxels which keep their unused status after the first step of the averaging algorithm will be used to construct cubical volumes with these voxels on the six surface layers.) Partially used voxels will not be labelled as used or valid during the first step.
used	any voxel that is entirely contained in the averaging cube of a valid voxel
valid	any voxel which is the centre of an averaging cube which contains ≤ 10 % of background material and has none of its faces completely embedded in background material



NOTE For the upper volume, the averaging cube is formed by the enclosed voxels (highlighted).

Figure 3 – Illustration of valid and used voxels in a valid averaging cube centred on the highlighted voxel and an invalid averaging volume for which a new cube has to be expanded about the surface voxel because it contains more than 10 % of background material

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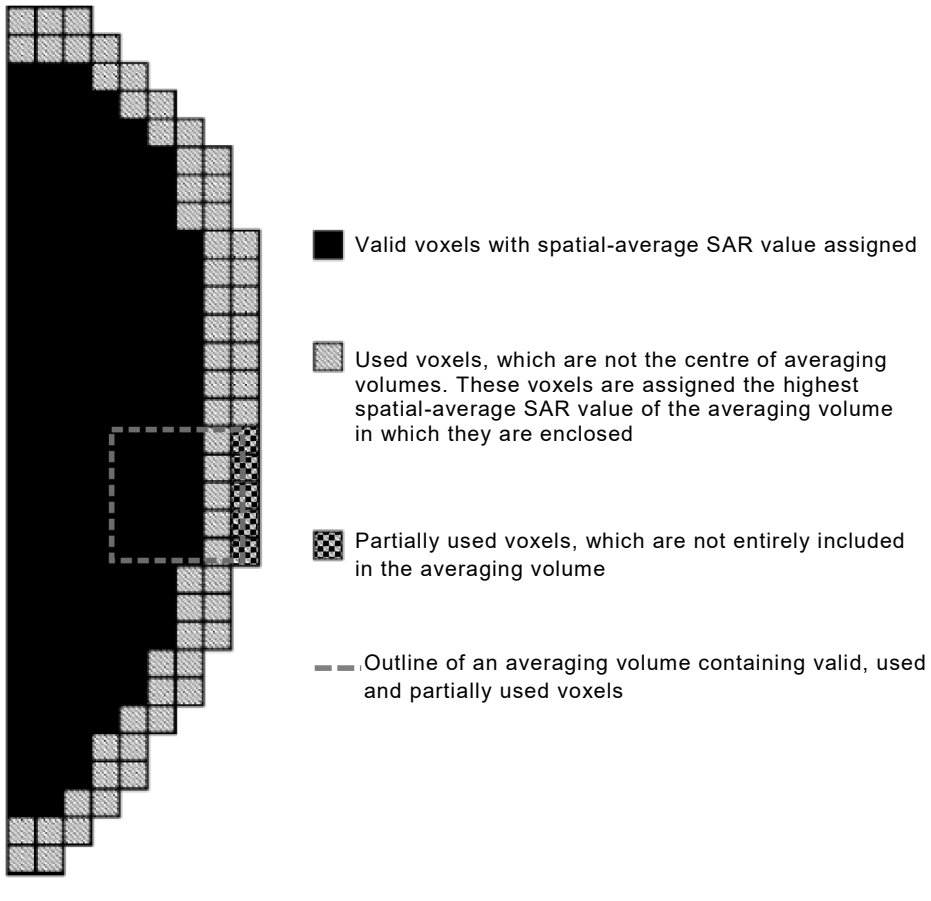

Figure 4 – Valid, used and partially used voxels

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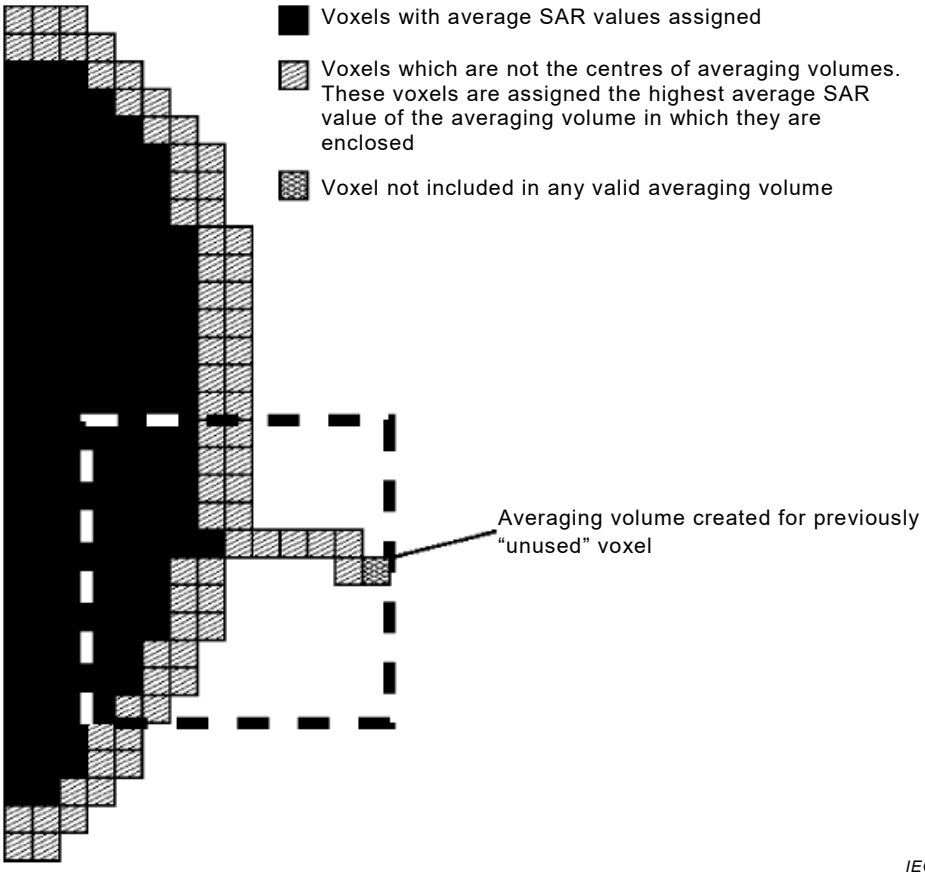

NOTE This figure shows a slice similar to the one shown in Figure 4, except for a body protrusion showing a distal "unused" voxel remaining from the first step of the averaging process. Also shown is the adjusted averaging cube created to include the previously unused voxel (centred at the exterior surface).

Figure 5 – "Unused" location

6.2.3 Calculation of the whole body average SAR

The whole body average SAR shall be calculated as the ratio of the power dissipated in all voxels consisting of tissues and fluids of the body divided by its total mass. The power dissipated in each voxel shall be calculated by multiplying the voxel SAR of Formula (8) by the voxel density ρ_{voxel}. The power dissipated in the whole body shall be calculated by summing up the dissipated power in all voxels of the body.

NOTE Possible uncertainties caused by round-off errors are considered in the evaluation of the power budget (7.2.5).

6.2.4 Reporting peak spatial-average SAR and whole body average SAR

The maximum value of the spatial-average SAR distribution, i.e. the peak spatial-average SAR, shall be reported together with its computational uncertainty for both body and extremity tissues. In addition, the coordinates of two corner points of the averaging cube shall be reported. The first corner point is defined by the minimum x-, y- and z-coordinates of all six corner points of the cube, the second corner point by its maximum x-, y- and z-coordinates. The whole body average SAR shall be reported with its computational uncertainty.

6.2.5 Referencing peak spatial-average SAR and whole body average SAR

Test results that are identified as compliant with the peak spatial-average SAR and whole body average SAR procedures of IEC/IEEE 62704-1 shall satisfy the definition of the FDTD algorithm of Clause 5 and the SAR averaging requirements of Clause 6. Moreover, the simulation software shall have passed the code verification of Clause 8. The peak spatial-

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