

# IEEE Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Head from Wireless Communications Devices: Measurement Techniques

IEEE Standards Coordinating Committee 39

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(Revision of  
IEEE Std 1528-2003)



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

Sponsor

**IEEE International Committee on Electromagnetic Safety**

Approved 14 June 2013

**IEEE-SA Standards Board**

**Abstract:** Protocols and test procedures are specified for the measurement of the peak spatial-average SAR induced inside a simplified model of the head of users of certain handheld radio transceivers. These transceivers are intended to be used for personal wireless communications services, operate in the 300 MHz to 6 GHz frequency range, and are intended to be operated while held against the ear. The results obtained by following the protocols specified in this recommended practice represent a conservative estimate of the peak spatial-average SAR induced in the head of a significant majority of persons, subject to measurement and other uncertainties that are defined in this recommended practice. The results are representative of those expected during conditions of intended use of a handheld wireless device. It is not the intent of this recommended practice to provide a result representative of the absolute maximum SAR value possible under every conceivable combination of head size, head shape, handset orientation, and spacing relative to the head. The measurement of SAR induced in the external tissues of the head, e.g., the external ear (pinna), is not addressed in this document. This recommended practice also does not address the body SAR measurements typically required for wireless handsets. The following items are described in detail: measurement concepts, measurement techniques, instruments, calibration techniques, simulated-tissue (phantom) models, including homogeneous anatomically equivalent models of the human head and simple phantoms for validation of the SAR measurement system, and the limitations of these systems when used for measuring the spatial-peak mass-averaged SAR. Procedures for calibrating electric field (E-field) probes used for SAR measurements and assessing the SAR measurement and system uncertainties are provided in the annexes. This recommended practice is intended primarily for use by engineers and other specialists who are familiar with electromagnetic (EM) theory and SAR measurement techniques; it does not recommend specific SAR limit values since these are found in other documents. The benefits to the users include standardized and accepted protocols, validation techniques, and means for estimating the overall measurement uncertainty in order to produce valid and repeatable data.

**Keywords:** handheld wireless transceivers, IEEE 1528™, miniature E-field probes, non-ionizing radiation, RF dosimetry, RF/microwave exposure assessment, RF/microwave hazard assessment, SAR measurement systems, SAR measurement uncertainty, specific absorption rate (SAR) measurements, wireless handsets

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## Introduction

This introduction is not part of IEEE Std 1528-2013, IEEE Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Head from Wireless Communications Devices: Measurement Techniques.

In June 1995, the IEEE Standards Board approved the establishment of Standards Coordinating Committee 34 (SCC34) as a collaborating effort with the Electromagnetic Energy Association.<sup>a</sup> Prior to 1995, assessment of exposure to various products was based on the procedures found in IEEE Std C95.3™-1991 [B100] that addresses exposure assessment in general but does not provide detailed procedures that could be applied to specific products.<sup>b</sup> In accordance with policies of the IEEE, SCC34 standards were issued and developed as IEEE standards, as well as being submitted to ANSI for recognition.

Subcommittee 2 (SC2) of SCC34 was established in February 1997 to develop standard protocols for evaluating certain wireless devices, such as handheld radio transceivers, wireless LANs, and similar devices, to meet specific SAR measurement criteria. The first version of IEEE Std 1528 was released in December 2003; an amendment was issued in 2005.

In March 2005, the integration of IEEE SCC34 into the IEEE International Committee on Electromagnetic Safety (ICES) was approved. Specifically, two former Standards Coordinating Committees, IEEE SCC28 and SCC34 were combined into a single Type 2 Standards Coordinating Committee (SCC39), called ICES. IEEE SCC34 is now ICES Technical Committee 34 (TC34), and it consists of two subcommittees: Subcommittee 1 (SC1) for measurement techniques, and Subcommittee 2 (SC2) for numerical techniques. Due to the joint meetings and common interests of the two Subcommittees, they share the same membership.

The scope of ICES TC34 is “The development of product performance standards relative to the safe use of electromagnetic energy for specific products that emit EM energy at frequencies between 0 and 300 GHz, i.e., the frequency range covered by the basic restrictions and maximum permissible exposure (MPE) values developed by the IEEE International Committee on Electromagnetic Safety (ICES).” ICES TC34 is responsible for this recommended practice. Although the scope of ICES TC34 covers a variety of devices, this recommended practice is devoted exclusively to handsets used for personal wireless communication services.

Standards developed by ICES TC34 are expressed in terms of easily measured parameters, e.g., output power, current, voltage, which are related to the basic restrictions and MPE values found in the latest revisions of standards such as IEEE Std C95.1™ and IEEE Std C95.6™ [B101].<sup>c</sup> Included in the scope are standards, guides, and recommended practices that describe measurement and computational protocols for evaluating the basic restrictions and derived limits found in the IEEE C95™ standards and in other relevant national and international standards and guidelines.

The SAR determined by following the procedures specified in this recommended practice is subject to measurement uncertainty and other uncertainties that are discussed in this document. This recommended practice does not address the measurement of SAR induced in the external tissues of the head, e.g., the external ear (pinna) and other parts of the body.

The purpose of this recommended practice is to provide a protocol for the measurement of the peak spatial-average SAR in an anatomically equivalent model of the human head of users of wireless handsets intended to be operated while held next to the ear. It provides the users with standardized and accepted protocols, measurement and validation techniques, and the means for estimating the overall measurement uncertainty in order to produce valid and repeatable data. Specific SAR limit values are not included since these are

<sup>a</sup> The Electromagnetic Energy Association was dissolved in 2000.

<sup>b</sup> The numbers in brackets correspond to those of the bibliography in Annex K.

<sup>c</sup> Information on references can be found in Clause 2.

found in other documents, e.g., the latest published versions of IEEE Std C95.1 and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) Guidelines.<sup>d</sup>

This revision extends the frequency range of IEEE Std 1528-2003 from 300 MHz to 3000 MHz to 300 MHz to 6000 MHz. Recently, there has been an increase in the development of personal wireless communication services in the 3 GHz to 6 GHz frequency range. Some of the technologies can be implemented in handsets and therefore SAR measurement protocols are needed to evaluate SAR according to exposure limits defined in international standards. IEEE Std C95.1-2005 states that for frequencies in the range 100 kHz to 6 GHz the evaluation of SAR may be used to demonstrate compliance with its specifications. SAR is the basic restriction for frequencies up to 3 GHz, and a transition frequency range of 3 GHz to 6 GHz allows compliance with the standard by evaluation of either incident power density or local SAR. Therefore, 6 GHz is the upper end of the frequency spectrum for which SAR evaluation is needed. While basic restrictions on SAR in the ICNIRP Guidelines go up to 10 GHz, the recommended practice in this revised IEEE standard was limited to an upper end frequency of 6 GHz since current wireless handsets operate below this frequency value.

An existing IEC standard has a scope that covers SAR measurements of devices held to the ear in the 300 MHz to 3000 MHz frequency range [IEC 62209-1, Human exposure to radio frequency fields from handheld and body-mounted wireless communication devices—Human models, instrumentation, and procedures—Part 1: Procedure to determine the specific absorption rate (SAR) for handheld devices used in close proximity to the ear (frequency range of 300 MHz to 3 GHz), published in 2005]. That standard was developed by the IEC, Technical Committee 106, Project Team 62209 (IEC TC106 PT62209). IEC TC106 PT 62209 has published a standard for devices near the body (not at the side of the head) in the 30 MHz to 6000 MHz range [IEC 62209-2, Human Exposure to Radio Frequency Fields from Handheld and Body-Mounted Wireless Communication Devices—Human models, Instrumentation, and Procedures—Part 2: Procedure to determine the Specific Absorption Rate (SAR) for wireless communication devices used in close proximity to the human body (frequency range of 30 MHz to 6 GHz), published in 2010]. The scope of this recommended practice is therefore a complement to IEC standards with a unique scope. ICES TC34 and IEC TC106 PT62209 have several common members and have held concurrent meetings. Both groups collaborate through a Category D Liaison to develop their respective standards and ensure that they are harmonized.

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<sup>d</sup> It is beyond the scope of this recommended practice to define what constitutes a hazardous radio frequency EM field. For commonly used basic restrictions and maximum permissible exposure values, refer to the latest versions of IEEE Std C95.1, the ICNIRP Guidelines, or other national requirements. It should be noted that limits given in these documents are under review and are subject to change as new information becomes available.

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# IEEE Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Head from Wireless Communications Devices: Measurement Techniques

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## 1. Overview

### 1.1 Scope

To specify protocols for the measurement of the peak spatial-average SAR in a simplified model of the head of users of handheld radio transceivers used for personal wireless communications services and intended to be operated while held next to the ear. It applies to contemporary and future devices with the same operational characteristics as contemporary devices that operate in the 300 MHz to 6 GHz frequency range and provides a conservative estimate<sup>1</sup> of the peak spatial-average SAR representative of that which

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<sup>1</sup> As used in this recommended practice, *conservative* means that the measured value will not be less than the expected value during normal use by a majority of users—it does not mean that the measured value will not be less than the absolute maximum SAR value that could possibly occur under every conceivable combination of head size, head shape, handset orientation, and spacing relative to the head.

would be expected to occur in the heads of a significant majority of persons during normal use<sup>2</sup> of these devices, but which may not be the absolute maximum value that could possibly occur under every conceivable combination of head size, head shape, handset orientation, and spacing relative to the head.

## 1.2 Purpose

The purpose of this recommended practice is to provide a protocol for the measurement of the peak spatial-average SAR in an anatomical model of the human head of users of wireless handsets intended to be operated while held next to the ear. It provides the users with standardized and accepted protocols, measurement and validation techniques, and the means for estimating the overall uncertainty in order to produce valid and repeatable data. Specific SAR limit values are not included since these are found in other documents, e.g., the latest published versions of IEEE Std C95.1™ and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) Guidelines.<sup>3</sup>

## 1.3 Background

Various national regulatory agencies, for example the Federal Communications Commission (FCC) in the US, require the peak spatial-average SAR of wireless handsets to be evaluated to ensure compliance with their rules (CFR Title 47 [B41] and guidelines of the FCC [B67], [B68]).<sup>4</sup> The SAR values adopted by different countries are usually based on standards such as IEEE Std C95.1 or guidelines such as those developed by ICNIRP (see Clause 2).

The SAR in a biological body exposed to a radio frequency (RF) field depends on a number of factors, including tissue geometry and dielectric properties and the orientation of the body relative to the source (Chou et al. [B31]). Since the RF energy induced in the body is scattered and absorbed at various tissue interfaces, the internal field and hence the SAR distribution is non-uniform. Energy coupling is complicated even further by source geometry and mutual coupling when the exposure is in the near field (Stuchly et al. [B190]), e.g., exposure conditions associated with handheld radio transceivers (Balzano et al. [B6]). Kuster and Balzano [B128] have shown that the peak spatial-average SAR values associated with the use of wireless handsets are mainly a function of the device geometry and square of the magnitude of the RF current density distribution on the device and the geometric position of the device relative to the head. Evaluating the SAR distributions associated with such devices is a complex task, usually accomplished by measurement techniques or numerical modeling. One means to evaluate compliance with specific SAR requirements is by measurement of the electric field (E-field) strength in a tissue-equivalent liquid using anthropomorphic models of the human head.

The current state-of-the-art regarding SAR assessment utilizes anthropomorphic-shaped phantoms made of a low-permittivity, low-loss plastic or fiberglass shell filled with homogeneous tissue-equivalent liquid. The phantom size and shape and the dielectric properties of the tissue-equivalent liquid used to represent average “head” tissue are chosen so that the measured SAR values are conservative, i.e., consistently exhibit a slight overestimation compared with heterogeneous anatomical head models.

The SAR in the tissue-equivalent liquid can be determined by the rate of temperature increase or by E-field measurements, according to Equation (1) or Equation (2):

<sup>2</sup> The difference between *normal use* and *intended use* is described in the NOTE of the definition of **intended use** in Clause 3.

<sup>3</sup> Information on references can be found in Clause 2.

<sup>4</sup> The numbers in brackets correspond to those of the bibliography in Annex K.

$$SAR_{\text{liquid}} = \left. \frac{c \Delta T}{\Delta t} \right|_{t=0} \quad (1)$$

$$SAR_{\text{liquid}} = \frac{\sigma |E|^2}{\rho} \quad (2)$$

where  $c$  is the specific heat capacity,  $\Delta T$  is the change in temperature,  $\Delta t$  is exposure duration,  $\sigma$  is the electrical conductivity,  $|E|$  is the rms magnitude of the E-field strength vector, and  $\rho$  is the mass density of the medium. As indicated in Equation (1), the SAR is determined from the initial slope of the temperature increase curve. When E-field measurements are used, the local (not spatially averaged) SAR is given by the energy absorption,  $\sigma |E|^2$ , divided by the local mass density  $\rho$ . The measured SAR values in a given liquid ( $SAR_{\text{liquid}}$ ) will differ from that in a standardized head medium ( $SAR_{\text{head}}$ ) by a constant factor given by the ratio of the density of the head medium,  $\rho_{\text{head}}$ , to the density of the liquid,  $\rho_{\text{liquid}}$ , as shown in Equation (3):

$$SAR_{\text{head}} = \frac{\rho_{\text{liquid}}}{\rho_{\text{head}}} SAR_{\text{liquid}} \quad (3)$$

For the purposes of this recommended practice, the standardized head medium density ( $\rho_{\text{head}}$ ) is set to 1000 kg/m<sup>3</sup>, with corresponding 1 g and 10 g averaging volumes of 1 cm<sup>3</sup> and 10 cm<sup>3</sup>, respectively. This density scaling is particularly important if thermally measured SAR is correlated with E-field probe readings, as is done in thermal calibrations of such probes. In that case, Equation (4) provides the correct density conversion:

$$SAR_{\text{head}} = \frac{\rho_{\text{liquid}}}{\rho_{\text{head}}} \underbrace{c_{\text{liquid}} \left. \frac{\Delta T}{\Delta t} \right|_{t=0}}_{SAR_{\text{liquid}}} \quad (4)$$

This recommended practice addresses the measurement of the peak spatial-average SAR associated with wireless handsets held next to the ear and operating at frequencies between 300 MHz and 6 GHz. The relevant characteristics and dynamic range of the SAR measurement system are as follows:

Frequency range: 300 MHz to 6 GHz

System dynamic range<sup>5</sup>: 0.01 W/kg to 100 W/kg

Probe-tip diameter:

- 8 mm or less for frequencies in the range 300 MHz to 2 GHz
- One-third of a wavelength (in the medium) or less for frequencies in the range 2 GHz to 6 GHz

Signal modulation:

- Unmodulated—continuous wave (CW)

<sup>5</sup> The dynamic range of 10 mW/kg to 100 W/kg allows the assessment of peak spatial-average SAR with a specified measurement uncertainty (see Clause 7) between 0.4 W/kg and 10 W/kg for pulsed signals with duty factors as low as 10%. A system that measures a peak SAR of 100 W/kg can only measure a time-averaged SAR of 10 W/kg for a signal with 10% or higher duty factor. The lower bound of the dynamic range (10 mW/kg) is defined based on the ambient noise limits established in 6.6.1.1 (12 mW/kg). If a system does not have a dynamic range capable of measuring SAR levels as low as 10 mW/kg, the ambient noise cannot be evaluated with the required accuracy.

- Periodic pulsed modulation 10 Hz to 1 kHz pulse repetition rates, and duty factors greater than 4%.<sup>6</sup>
- Random noise-like digital modulations such as those used in code-division multiple access (CDMA) and similar configurations.<sup>7</sup> See E.2.5 for more information on modulation uncertainty

For SAR evaluation of wireless handsets using tissue-equivalent liquids representative of high-water content tissues, the typical dynamic range of an E-field probe extends from approximately 3 V/m to 350 V/m, which corresponds to a range in temperature rise of 3  $\mu$ K/s to 40 mK/s. While temperature-increase measurements using temperature probe or infrared camera techniques have been widely used in research or for transfer calibrations, these methods are not suitable for testing low-power devices because of their limited sensitivity and dynamic range. Only miniature E-field probes with diode-loaded dipole sensors can provide the required dynamic range, and therefore, the handset test procedures described in this recommended practice are limited to measurement techniques using miniature E-field probes. Other types of E-field probes with sufficient sensitivity and spatial resolution, e.g., electro-optical devices, are being investigated but have limited commercial availability at present (Iyama et al. [B108]).

SAR measurements are carried out by scanning within a thin anatomically based phantom shell filled with a tissue-equivalent liquid, typically using a multi-axis robot to position a miniature E-field probe. Once the regions of highest SAR are identified, post-processing algorithms subject to the requirements described in this document shall be used to average the local SAR over a prescribed volume to determine the peak spatial-average SAR (see for example Balzano et al. [B5]; Schmid et al. [B182]; Wojcik and Cardinal [B203]; Yu et al. [B205]).

Clause 3 contains definitions for specific terms used in this recommended practice and for general terms used in electromagnetic (EM) theory and measurement. Clause 4 and Annex A describe the probe system instrumentation characteristics needed for assessing local SAR in shell phantoms filled with tissue-equivalent liquids. Deviations from ideal performance of the probes and signal-acquisition electronics and effects on the uncertainty of the peak spatial-average SAR assessment are described. Procedures for calibration and uncertainty assessment are also described.

Clause 5 defines the physical characteristics of the reference head model, including shape and dimensions. A flat phantom used for system validation is also described. Characteristics of the external ear and hand are discussed as applied to developing the head phantom and device test protocols. The dielectric properties of the phantom material (tissue-equivalent liquid) are given. Methods that can be used to verify the dielectric properties of the tissue-equivalent liquid are provided in Annex B. Some available recipes for achieving the target dielectric parameters are provided in Annex C. More information about the geometry of the head model is provided in Annex D.

Clause 6 describes the measurement protocols for determining the peak spatial-average SAR including: instrumentation setup protocol, device operational conditions, device positioning at the phantom, SAR distribution and E-field scanning procedures, fast SAR procedures, test reduction procedures, and post-processing interpolation and extrapolation algorithm requirements.

Clause 7 and Annex E discuss the necessary documentation of specific supporting information to demonstrate that a device has been evaluated correctly for SAR requirements, e.g., descriptions of evaluation procedures, device test configurations, measurement results, and explanations of data analysis methods. Evaluation methods for uncertainty of each of the contributing components and the total measurement uncertainty are discussed in detail in Annex E. Annex F provides related tutorial information about measurement uncertainty.

<sup>6</sup> The required range of repetition rates and duty factors covers the repetition rates and duty factors presently used for mobile communication systems.

<sup>7</sup> This recommended practice includes general requirements for modulation specific probe calibration (see A.1 and A.2). The specific signal characteristics used in probe calibrations and the applicability for measuring the SAR of test devices with somewhat different or varying signal characteristics may require investigation in future revisions.

Clause 8 describes the methods and procedures used for the system check and system validation. Recommendations for interlaboratory comparisons of SAR measurement results are also provided. Annex G describes construction details for reference sources used in the routine system check and system validation.

Annex H provides information about fast SAR test methods using different hardware from those described in Clause 6, and it includes examples of the use of the fast SAR protocols defined in Clause 6. Annex I provides additional information on SAR test reduction in support of the procedures defined in Clause 6. Annex J provides supporting examples of the general SAR test procedures defined in Clause 6.

## 1.4 Rationale

This recommended practice describes test methods that are used to simulate the exposure of a reasonable cross section of users associated with the operation of contemporary wireless handsets when held next to the ear. In the following discussions the terms “reasonable cross section of users” and “significant majority of persons” are used to refer to any population that can be characterized adequately by the phantom described as follows. Although individual persons vary considerably in features, it is important to have a well-defined reference phantom model with which to perform peak spatial-average SAR measurements. A reference phantom allows results from all laboratories to be compared without differences between phantoms that can introduce variations in results.

The specific phantom, the dielectric properties of the tissue-equivalent liquid, and the specific test positions were chosen to provide a conservative estimate of the SAR. The two operating positions defined by the test procedures, each tested on both sides of the head according to test and handset operating configurations established in this recommended practice, are intended to cover a reasonable cross section of conditions consistent with the intended use of the handset.

### 1.4.1 Specific Anthropomorphic Mannequin (SAM)

The rationale for choosing the specific head phantom model (i.e., SAM) described in this recommended practice is based on the following criteria:

- a) The peak spatial-average SAR shall be a conservative estimate of the actual value expected to occur in the heads of a significant majority of persons during the intended use of wireless handsets.
- b) The test results shall not unnecessarily overestimate the peak spatial-average SAR expected in actual users.
- c) The phantom shall allow stable and repeatable device positioning for peak spatial-average SAR measurements and be effective for verifying repeatability and reproducibility via interlaboratory comparisons.
- d) The phantom shall be practical for routine SAR evaluation.
- e) The phantom shall satisfy these criteria for contemporary and future handset designs and be unbiased with respect to any particular handset design or shape.

Based on the presently available science, literature, and experience, the design of a phantom that meets the preceding criteria, especially item a) provides a conservative estimate of the actual SAR, which is a function of at least the following parameters:

- Head size and shape of the phantom shell, and homogeneity of the tissue-equivalent liquid.
- Electrical parameters of head tissue-equivalent liquids and phantom shell.

- Ear pinna/auricle size, shape, location and material properties.
- Exclusion of the hand for measuring SAR in the head (see 5.2.5 for more information).

Although strictly not a part of the conservative attributes of the SAM phantom, the physical and electrical characteristics and operating frequencies of different handsets and sources are important regarding general conservative overestimate conditions (Kuster et al. [B131]). The criterion for the phantom to be unbiased with respect to handset design means in part that handset designs that produce lower assessed SAR values correspond to reduced exposure in real-world situations, and vice versa. The peak spatial-average SAR value varies greatly between different handset designs because the RF current (distribution and magnitude) flowing on the antenna and handset is determined by the design and separation between the phantom and current-carrying device elements and features. Relevant handset design features include shape, size, curvature, clamshell and other case types, antenna type, placement of any RF components, circuit traces and matching circuits, and antenna loading by phantom features. More discussion is given in 1.4.1.5.

The collective impact of the above parameters is to produce a margin such that the SAR values assessed using the test procedures of this standard are expected to be higher than during actual use conditions of a handset. SAR overestimation can never be established for all possible head, device, and positioning configurations. In order that the results are not overly conservative, and thereby unnecessarily inhibit the advancement of new wireless communications technologies, SAR overestimates should be as small as possible. Achieving an optimal compromise between overestimated or underestimated conditions is a complex task, which is why the conductivity of the tissue-equivalent liquid is selected to provide the required overestimation. Further discussion is included in 1.4.1.5 and Clause 5 on how the homogeneous SAM phantom was derived to overestimate peak spatial-average SAR. Validation of the SAM model by ICES TC34 members and other groups is described in 1.4.1.5.

Several homogeneous phantom shapes were previously considered by IEEE Standards Coordinating Committee (SCC) 34 (now ICES TC34) before selecting SAM for IEEE Std 1528-2003, including the following:

- Existing anthropomorphic phantoms
- Rectangular flat phantom
- Spherical phantom
- New design of anthropomorphic phantom

A closest-spacing condition is best provided by a flat phantom. However, compared with a real head, the flat phantom model may cause considerable changes in antenna loading and impedance due to improper antenna spacing to the head. Spherical phantoms of appropriate diameter better resemble the proper antenna spacing in the head posterior region. However, the coupling of energy into the phantom and the loading of the mobile phone antenna is best represented by an anthropomorphic shape. Therefore, IEEE SCC34 (now ICES TC34) decided to use a “human-like” or anthropomorphic shape. Due to the diversity of existing phantom shapes, volumes, and shell thicknesses, the decision was made to develop a new design of an anthropomorphic phantom. All design details and dimensions are contained in a publicly available computer-aided design (CAD) file,<sup>8</sup> to allow uniform reproduction and manufacture by multiple vendors.

<sup>8</sup> The CAD model is for use in the basic manufacture of the SAM phantom standard test fixture by groups having the necessary expertise and resources. Four \*.igs files of inner and outer surfaces for the left and right halves extracted from the CAD model of the SAM phantom are provided with this standard at <http://standards.ieee.org/downloads/1528/1528-2013/>. The four file names are:

- 1) << File: sam\_lft\_in\_6\_11.igs >>
- 2) << File: sam\_lft\_out\_6\_11.igs >>
- 3) << File: sam\_rt\_in\_6\_11.igs >>
- 4) << File: sam\_rt\_out\_6\_11.igs >>

The file formats are Initial Graphics Exchange Specification (\*.igs), an ASME/ANSI standard for the exchange of CAD data that is independent of any software package. For convenience, the files are also provided in STL (stereo lithography) format which have been derived from the original \*.igs files. Because the SAM phantom file is a 3-dimensional CAD model, it requires a 3-D CAD viewer. For users without access to a full-feature CAD package, various limited usage 3-D CAD viewers are available for free download on the Internet.

Based on committee consensus, available knowledge, and experience, after extensive deliberations and design iterations, the final version of the SAM phantom adopted for IEEE Std 1528-2003 is also used for this revision of IEEE Std 1528.

#### 1.4.1.1 Head size

Results presented in Hombach et al. [B95], Kuster and Balzano [B128], and Schönborn et al. [B183] showed that the peak spatial-average SAR is not significantly dependent on the head size, provided that the geometrical relationships between the handset and the head are the same. A head geometry that provides overall smaller distances between the handset and the tissue boundary will provide more conservative results because the separation between the equivalent current elements on the device under test (DUT) and the tissue-equivalent liquid will be less. Thus, a larger anthropomorphic head model, with larger local radii of curvature, will satisfy the criterion for minimal distances.

One existing phantom, for example, was designed such that the distance between the handset and liquid was always smaller than in 90% of the sample population for a given set of handset positions (Kuster et al. [B131]). Following the same approach, the derivation of the internal and external shapes and sizes of the SAM model was based on selected dimensions from the much larger anthropometric database of 1774 US Army males (Gordon et al. [B84]). It is important to note that SAM does not represent a “90th-percentile head,” because a head that possesses all of the 90th-percentile dimensions does not exist. Rather, SAM has been derived from a selected relevant subset of the 90th-percentile male head data.

#### 1.4.1.2 Phantom shape

As shown in Kuster and Balzano [B128] and Christ et al. [B38], [B35], the peak spatial-average SAR values associated with the use of wireless handsets is mainly a function of the geometry, the magnitude-squared of the RF current density distribution on the device and the geometrical positions of the maximum current densities relative to the head. The distances between each point of the handset and the closest tissue boundary can only be simulated independent of handset design if the entire head shape is suitably simulated. The requirements that the measured results are a conservative estimate and are unbiased with respect to handset design are met with an anthropomorphic head shape, because an anthropomorphic shape will appropriately simulate the geometrical relationships between a human head and a handset. As mentioned above, the dimensions and shape of SAM, except for the ear protrusions discussed later, were derived from a subset of the 90th percentile dimensions from the survey of the US Army males. The anthropometric dimensions used in the development of SAM are tabulated in Annex D. Some head surface features not specified in the Army data were extrapolated between the referenced dimensions, such as the nose, cheeks, and eye sockets.

#### 1.4.1.3 Head tissue-equivalent liquid

In order to satisfy the criterion for practical SAR evaluation with scanned E-field probes, the head shall be simulated as a homogeneous liquid, rather than as a multi-layered or high-density solid. To fulfill the conservative criteria in SAR assessment, the homogenous liquid parameters shall be carefully selected taking into account the energy coupling enhancement due to standing waves that occurs in tissue layers of the human head. The tissue-equivalent liquids for the 300 MHz to 3000 MHz frequency range described in Clause 5 are based on a study of the anatomical variations in the ear region for a cross section of a representative user population<sup>9</sup> (Drossos et al. [B60]). Extrapolation to 6000 MHz was performed as explained in 5.4.1. At each frequency, the possible ranges of layered-structure thickness and conductivity of the tissue-equivalent liquid that resulted in the highest peak spatial-average SAR values (1 g and 10 g average) were evaluated. Dielectric properties for homogeneous head tissue-equivalent liquids were

<sup>9</sup> Conservativeness of tissue-equivalent dielectric parameters for the head region in the lower cheek, mouth, or jaw regions for current generation handsets has not been studied.

determined to produce the same (or slightly higher) peak spatial-average SAR values compared to the highest values occurring in the heterogeneous cases. The suitability of the proposed values for the dielectric properties of the tissue-equivalent liquid was assessed at 900 MHz and 1800 MHz (Monebhurrin et al. [B156]). At frequencies in the 3000 MHz to 6000 MHz range, dielectric parameters were extrapolated as explained in 5.4.1.

#### 1.4.1.4 Pinna shape, orientation, and thickness

In the selection of any phantom for handset SAR testing, a properly designed and positioned pinna (external ear) is necessary in order to achieve correct and repeatable geometrical relationships between the handset and the tissue boundary. The shape, orientation, and thickness of the pinna define the geometrical relationship between handset and head tissue, and these properties are as critical as the head shape.

A properly oriented pinna spacer included on the head phantom would allow the peak spatial-average SAR assessment to be unbiased with respect to the shape of a specific handset. For typical human heads, the compressed pinna naturally slopes toward the anterior (front) side, i.e., the thickness of the pinna at the anterior side is less than at the posterior side. This characteristic is reflected in the SAM phantom.

A human pinna is composed of complex cartilage that forms air cavities. The concha, the largest air volume in the center of the pinna, funnels sound into the ear canal. The pinna provides a natural spacer between the head tissue and handset. The small intermediate quantity of ear tissue may absorb RF energy if the handset equivalent current density is proximate to this specific area. This type of absorption in the pinna is possible in many modern small handsets. However, for some handsets the maximum SAR is induced in locations other than near the pinna. For SAM, the pinna orientation and shape were selected to maximize the inductive coupling from a handset to the head. Since human pinnae are never fully compressed, with the prevailing style of supra-concha handsets, a natural air spacer (except for the bridging cartilage) is created.

IEEE SCC34 (now ICES TC34) reviewed results from several investigations of various pinna shapes and compositions (see 5.2.4). None of those studies were conclusive enough to justify introducing the necessarily complex measuring techniques with a corresponding reduction in repeatability that would accompany a detailed pinna model. Therefore, it was decided to simulate the pinna using a stable, simplified loss-less spacer with a thickness of 6 mm (including the 2 mm phantom shell thickness). This spacer thickness is considerably less than the typical 19 mm to 28 mm spacing between the rear edge of the pinna (when not compressed) and the head shown in the anthropometric data as tabulated by the US Army (Gordon et al. [B84]), thereby contributing to the conservative conditions of SAM for head SAR assessments.

#### 1.4.1.5 Phantom validation

The phantom validation process involves comparison of numerically modeled SAR in heterogeneous head models and homogeneous phantoms, followed by validation of the numerical phantom models by measurements. Because the intent is a relative comparison of the various head representations, the validation process uses simplified source models. High-resolution, detailed handset models do not provide further insight to the phantom validation process. In order to validate the SAM phantom and verify that measurements made using it would represent a conservative evaluation of the maximum local SAR induced in an actual human head by several generic handsets, comparisons were made between computed SAR values induced in highly detailed heterogeneous head models using the latest tissue dielectric parameters from the available literature (e.g., Hasgall et al. [B92]) and the SAR induced in a computer model of the SAM phantom.

In earlier studies, SAR evaluations were performed for several antenna types using heterogeneous magnetic resonance imaging (MRI)-based head models. The antenna types include quarter-wave ( $\lambda/4$ ) monopoles, half-wavelength ( $\lambda/2$ ) dipoles (Dimbylow [B52]; Dimbylow and Mann [B53]; Watanabe et al. [B200]), and

other lengths (Gandhi et al. [B83]) of either antenna mounted on various sizes of simplified handset-like box models. Helical monopoles on a handset box, and internal patch-type and planar-inverted-F antennas (PIFA) mounted on the rear or side of a handset box, have also been investigated. These studies cannot be utilized for SAM validation because the device test configurations are different from that established by SAM; therefore, the results are not comparable.

Only the results of more recent studies designed to compare the SAR values induced in heterogeneous head phantoms to the values induced in SAM can be used to demonstrate the validity of the SAM phantom. A study was reported in Christ et al. [B36] with different generic handsets either equipped with helical or  $\lambda/4$  monopole antennas operating at frequencies of 900 MHz and 1800 MHz and placed in the cheek and tilt positions described in Clause 6. In this study, the SAR values induced in SAM were compared with those induced in a highly detailed MRI-based heterogeneous phantom (minimum voxel size 0.125 mm<sup>3</sup>). The pinna of this phantom was collapsed to only 4 mm thickness in order to represent a closest-spacing scenario. In addition to the Clause 6 positions, handsets with the peak equivalent filament current densities in the vicinity of the display area were simulated in Christ et al. [B32] by shifting the handset box with wire or helical monopoles along the B-M line of SAM (see Figure 6) towards the mouth. The SAR overestimation shown in Christ et al. [B32] ranged from 5% to over 150%. A more recent study has confirmed these results using a model of a commercially available handset (Chavannes [B28]). These studies at 900 MHz and 1800 MHz were used to validate the conservative characteristics of SAM at the most common handset frequencies, and therefore the concepts and criteria from which the SAM phantom was derived. The same rationale can be applied to the 300 MHz to 3 GHz frequency range because it was generally expected that SAM provides conservative SAR values over that entire frequency range. A thorough analysis of SAR in different head models at 835 MHz and 1900 MHz by an international group of 14 governmental, academic, and industrial research organizations found that SAM produced a higher SAR than anatomical adult and child models when the SAR in the pinna is calculated separately from the SAR in the head (Beard et al. [B10]).

This work has been extended to frequencies in the 300 MHz to 6000 MHz range. The results obtained from the participating nine organizations show that the SAR produced in SAM for this frequency range is higher than the head SAR in the anatomical adult and child head models. The details of this study are reported in Bit-Babik [B13]. The considerations given in 5.2.2 requiring the shape of SAM to produce conservative SAR measurement results are supported by the head SAR results in this study for most frequencies. However, the SAR values computed for the pinna and the head in the anatomical head models in comparison with the SAR computed in SAM were less conclusive at 2450 MHz and 3500 MHz. For example, with reference to the IEEE Std C95.1-2005, the pinna SAR values at these two frequencies were on average, respectively, 13% and 23% higher for the child model than the SAR in SAM. When compared to ICNIRP and IEEE Std C95.1-1991, the pinna SAR for the child head model was also higher than the head SAR in SAM. The pinna SAR for the adult head model was respectively 25% and 21% lower than the SAR in SAM at these two frequencies. The range of differences could be attributed to pinna variability and other anatomical features among adult and child head models. Further studies with the use of additional realistic anatomical head models will be necessary in order to clarify the conservativeness of SAM relative to SAR produced in the pinna and the head.

#### 1.4.2 Test positions

The criteria used by ICES TC34 to select a range of handset test positions are as follows:

- a) The number of test positions shall be a minimum for representing typical conditions and configurations.
- b) The positions shall appropriately reflect the operational configurations and intended use positioning of the handset next to the ear so as to produce a conservative estimate of SAR for a reasonable cross section of users.
- c) The positions shall be unbiased with respect to any particular phone design.

- d) The test positions, along with the SAM phantom, shall enable high reproducibility of SAR measurements and be describable and usable to verify repeatability and reproducibility via future interlaboratory comparisons.

Because variations in position may cause significant variations in peak spatial-average SAR, the protocol shall be written such that the handset is tested for the expected variations of the intended use position. Based on available information and experience, IEEE SCC34 (now ICES TC34) established consensus by selecting four operating positions, specifically the “cheek” and “tilt” positions at the ear on the left and right sides of the SAM phantom. These positions produce results that are representative of typical exposures expected to occur in the heads of a significant majority of persons during the intended use of handheld wireless devices, but may not be representative of a worst-case position. A worst-case position may be outside of the range of intended use positions and difficult to determine within a reasonably finite number of tests.

As described in 1.4.1.2, the peak spatial-average SAR is mainly a function of the geometry of the RF current density distribution on the device and its geometric separation from the lossy head tissue. RF currents on the handset, e.g., the device case or the antenna, induce currents in the head. Since the handset case is in contact with the face in the cheek position, this position represents a conservative test condition for all handsets with substantial RF currents on or within the device case. The tilt position represents a conservative test condition for all handsets with equivalent maximum current density in regions above the acoustic output, including external antennas (Kuster [B127]).

The cheek position can be described independently of the handset design, i.e., contact with the phantom is always maintained at two or more points, and this position provides the best positioning repeatability. It further reflects the most conservative condition for exposure associated with equivalent maximum current densities on the device case. The tilt position was defined on the basis of CENELEC/WGMTE (Working Group on Mobile Telecommunication Equipment) reviews of various handset usage surveys. For most flat handsets, the tilt position corresponds approximately to the “100°” position of CENELEC ES 59005:1998 [B27].

From 1997 through 2001, various test labs and IEEE SCC34 members evaluated a large number of devices in accordance with CENELEC ES 59005:1998 [B27] recommendations. The ES 59005 recommendations use four positions: cheek, intended, 100°, and tilted (90°/30° tilted). An analysis of the results on 50 devices (Kuster et al. [B131]; Kuster [B127]) showed that only two cases in the “intended” or “tilted” positions have maximum peak-spatial SAR values greater than 10% of the value obtained in the cheek or 100° positions. These findings are a function of the current distributions and are not expected to be very sensitive to the ear shape and spacing. From these results (Kuster et al. [B131]), and an examination of SAR as a function of tilt angle with respect to the Reference Plane and a line through the two ear reference points (see Clause 5), IEEE SCC34 concluded that the four positions per side defined in CENELEC ES 59005:1998 [B27] could be reduced to two positions per side without affecting the requirement for a conservative assessment of user exposure (Kuster [B127]). These two positions are also used in this revision.

## 2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in the text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

“ICNIRP Guidelines for Limiting Exposure to Time-varying Electric, Magnetic and Electromagnetic Fields (up to 300 GHz),” *Health Physics*, Vol. 74, pp. 494–522, 1998.<sup>10</sup>

IEEE Std 1309™-2005, IEEE Standard for Calibration of Electromagnetic Field Sensors and Probes, Excluding Antennas, from 9 kHz to 40 GHz.<sup>11, 12</sup>

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

IEEE Std C95.1™-2005, IEEE Standard for Safety Levels With Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz.

IEEE Std C95.3™-2002, IEEE Recommended Practice for Measurements and Computations of Radio Frequency Electromagnetic Fields with respect to Human Exposure to Such Fields, 100 kHz to 300 GHz.

### 3. Definitions and special terms

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* [B99] should be consulted for terms not defined in this clause.<sup>13</sup>

#### 3.1 Definitions

**anechoic chamber:** An enclosure especially designed with boundaries that absorb sufficiently well the sound or electromagnetic (EM) energy incident thereon to create an essentially free-field condition in the frequency range of interest.

**antenna:** That part of a transmitting or receiving system that is designed to radiate or to receive electromagnetic (EM) waves.

**antenna driving point:** That part of the radiating structure where the RF currents start to support the electromagnetic (EM) fields that carry energy away from the antenna. 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 RF 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.

**antenna feed-point impedance (terminal or driving-point impedance):** The 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.

**anthropometric:** Refers to comparative measurements of the human body relative to specified populations.

**anthropomorphic:** Having a human-like form or attributes.

<sup>10</sup> International Commission on Non-Ionizing Radiation Protection (ICNIRP) publication available at <http://www.icnirp.de/documents/emfgdl.pdf>.

<sup>11</sup> The IEEE standards or products referred to in Clause 2 are trademarks of The Institute of Electrical and Electronics Engineers, Incorporated.

<sup>12</sup> IEEE publications are available from The Institute of Electrical and Electronics Engineers (<http://standards.ieee.org/>).

<sup>13</sup> *IEEE Standards Dictionary Online* subscription is available at:  
[http://www.ieee.org/portal/innovate/products/standard/standards\\_dictionary.html](http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html).

**attenuation:** A general term, expressed as a ratio, used to denote a decrease in magnitude of a field quantity in the transmission from one point to another.

NOTE—The attenuation may be expressed as a scalar ratio of the input magnitude to the output magnitude or in decibels.<sup>14</sup>

**average power ( $\bar{P}$ ):** The time-averaged rate of energy transfer is shown in the following equation:

$$\bar{P} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} P(t) dt \quad (5)$$

where  $P(t)$  is the instantaneous power. The time duration could be source related (e.g., the source repetition period, duty cycle) or use related (e.g., the averaging time specified in exposure guidelines).

NOTE—See Equation (5).

**average power output, amplitude-modulated transmitter:** The radio frequency (RF) power delivered to the transmitter output terminals averaged over a modulation cycle.

**band:** The frequency range associated with a specific operating mode.

NOTE 1—An operating mode may have several frequency bands allocated for it e.g., GSM<sup>®</sup> mode uses 850 MHz, 900 MHz, 1800 MHz, and 1900 MHz bands.<sup>15</sup>

NOTE 2—The frequency band is usually referred to using rounded figures, however the actual frequency allocation may be slightly different, e.g., GSM 850 MHz band actually uses 824 MHz to 849 MHz and 869 MHz to 894 MHz, GSM900 MHz band actually uses 880 MHz to 915 MHz and 925 MHz to 960 MHz.

**benchmark test:** A procedure or test that can be used to compare systems or components to each other or to a standard.

**boundary effect (probe):** A change in sensitivity of an electric field (E-field) probe when the probe is located close to media boundaries (less than one probe-tip diameter).

NOTE—The boundary effect can be a major source of error. Computer simulations and measurements show that in shell phantoms filled with tissue-equivalent liquids, the error due to boundary effects is typically less than 2% if the distance between the probe tip and the surface is greater than one probe tip diameter.

**channel:** a specific logical sub-division of the available frequency range in use by an operating mode.

NOTE—The number of channels and the specific size (expressed as frequency or time) will vary with operating mode and operating band. For the purpose of this standard only the channels to identify and locate the start, mid point and end of the operating frequency band are used.

**complex permittivity ( $\epsilon$ ):** The ratio of the electric flux density in a medium to the electric field (E-field) strength at a point. The permittivity of biological tissues is frequency dependent. Permittivity is a complex quantity and it is expressed in units of farad per meter (F/m).

**concha:** The largest and deepest concavity of the external ear (pinna).

<sup>14</sup> Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

<sup>15</sup> GSM is registered and owned by the GSMA. This information is given for the convenience of users of this standard and does not constitute an endorsement by the IEEE of these products. Equivalent products may be used if they can be shown to lead to the same results.

**conductivity ( $\sigma$ ):** The ratio of the magnitude of the conduction-current density in a medium to the electric field (E-field) strength. Conductivity is expressed in units of siemens per meter (S/m).

NOTE—In the general case conductivity is a complex tensor quantity.

**coverage factor:** A factor  $k$  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. Specifically,  $k \times (\text{combined uncertainty}) = (\text{expanded uncertainty})$ . When  $k = 1$ ,  $P \sim 0.68$ ;  $k = 2$ ,  $P \sim 0.95$ ;  $k = 3$ ,  $P \sim 0.999$ .

**device holder:** A fixture constructed of low-loss dielectric material that is used to hold the handset-under-test in the required position during measurement.

**dielectric constant:** *See:* **complex permittivity; relative permittivity.**

**diode:** A semiconductor device having two terminals and exhibiting a nonlinear voltage-current characteristic; in more restricted usage, a semiconductor device that has the asymmetrical voltage-current characteristic exemplified by a single p-n junction.

**dipole (antenna):** **(A)** A linear radiator, usually fed in the center, producing a maximum of radiation in the plane normal to its axis. The length specified is the overall length. **(B)** Any one of a class of antennas producing the radiation pattern approximating that of an elementary electric dipole.

NOTE—Common usage considers a **dipole antenna** to be a metal radiating structure that supports a line-current distribution similar to that of a thin straight wire, one-half wavelength long, so energized that the current has a node only at each end.

**duty cycle:** *See:* **duty factor.**

**duty factor:** The ratio of the pulse duration to the pulse period of a periodic pulse train.

**electric dipole:** A pair of equal and opposite charges separated by an infinitesimal distance. When the charges are oscillating, the dipole becomes an elementary radiating electric dipole.

**electric field (E-field):** A vector field of E-field strength or of electric flux density.

NOTE—This term is also used to denote a region in which such vector fields have a significant magnitude.

**electric field (E-field) probe:** A minimally perturbing structure containing an electrically small E-field sensor, or a set of multiple E-field sensors, and the components necessary to transform the sampled radio frequency (RF) signal into a proportional direct current or voltage. An elemental E-field probe consists of a thin dielectric substrate containing a sensor, such as an electrically short (in tissue) dipole, a diode to rectify the RF signal and a balanced high-resistance transmission line to extract the rectified signal. The dipole elements and the high resistance leads are usually applied to the substrate using thin film techniques; diodes and any other discrete components are bonded to the thin film elements. An isotropic probe consists of three such devices arranged in a “ $\Delta$ ” (triangular) -beam configuration (preferred) with the axis of each dipole orthogonal to the axes of each of the others, e.g., aligned along the diagonals of a cube.

**electric field (E-field) strength ( $E$ ):** **(A)** (general) 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. **(B)** (signal-transmission system) The magnitude of the potential gradient in an E-field expressed in units of potential difference per unit length in the direction of the gradient. **(C)** (radio wave propagation) The magnitude of the E-field vector. E-field strength is expressed in units of volt per meter (V/m).

NOTE—This may be measured either in newtons per coulomb or in volts per meter. 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.

**electric field (E-field) vector:** The force on a stationary positive charge per unit charge.

**electric flux density (displacement):** A vector equal to the product of the electric field (E-field) strength and the permittivity of the medium. In an anisotropic medium, the permittivity is a function of direction; hence, the electric flux density is not necessarily in the same direction as the E-field. Electric flux density can be considered as a surface charge density and is expressed in units of coulomb per square meter (C/m<sup>2</sup>).

**electrical length:** The length of any electrical conductor, such as an antenna or transmission line, expressed in wavelengths, radians, or degrees, in any medium including air.

NOTE—When expressed in angular units, electrical length is distance in wavelengths multiplied by  $2\pi$  to give radians, or multiplied by 360 to give degrees.

**electromagnetic (EM) field:** EM phenomena expressed in scalar or vector functions of space and time, e.g., a time-varying field associated with electric and magnetic forces and described by Maxwell's equations.

**far-field region:** That region of the field of an antenna where the angular field distribution is essentially independent of the distance from the antenna. In this region (also called the *free-space region*), the field has a predominantly plane wave character, i.e., locally, very uniform distributions of electric field (E-field) strength and magnetic field strength in planes transverse to the direction of propagation. For larger antennas especially, the far-field region is also referred to as the *Fraunhofer region*.

**feed point (antenna):** *See:* **antenna driving-point**.

**finite-difference time-domain (FDTD) method:** A numerical algorithm for solving Maxwell's differential equations of electromagnetic (EM) field interactions in the time domain by discretizing the problem space into unit cells where the space and time derivatives of the electric and magnetic fields are directly approximated by simple, second-order, accurate, central-difference equations.

**handset:** A handheld device consisting of an earphone and a microphone intended to be operated next to the side of the head and acoustically coupled to the ear.

NOTE 1—*See:* **handheld** in 3.2.

NOTE 2—For purposes of this recommended practice, an assembly to be held in the hand of the user that includes a radio transmitter and receiver.

**heat capacity:** The amount of heat necessary to raise the temperature of a given mass (not a specific unit mass) of a substance one degree. Heat capacity is expressed in units of joules per kg per kelvin (J/kg K) or joules per kg per degree Celsius (J/kg °C). *See also:* **specific heat capacity**.

**holder, device:** *See:* **device holder**.

**incident wave:** A wave, traveling through a medium, in a specified direction, which impinges on a discontinuity or a medium of different propagation characteristics.

**insertion loss:** The loss resulting from the insertion of a component in a transmission system. It is the ratio of the power delivered to the load when connected to the generator, to the power delivered to the load when the component is inserted. Insertion loss is usually expressed in decibels (dB).

**intended use:** The use of a device, over its full range of functions, in accordance with the instructions provided by the manufacturer, including instructions on operating position and orientation.

NOTE—**Intended use**, i.e., the way a manufacturer specifies that a device should be used, and the way that a device is normally used may not be the same.

**isotropic probe:** A hypothetical probe capable of receiving equally well in all directions and equally responsive to all polarizations of electric and/or magnetic fields.

**loss tangent:** The ratio of the imaginary component of the complex permittivity of a material to the real component of the complex permittivity.

**magnetic field strength ( $H$ ):** The magnitude of the magnetic field vector, expressed in units of amperes per meter (A/m). 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  $\mu$ , i.e.,  $H = B/\mu$ .

**magnetic field (H-field) vector:** A field vector that is equal to the ratio of the magnetic flux density to the permeability, expressed in units of A/m.

**magnetic flux density:** A vector quantity that describes the force per unit charge on an infinitesimal charge at a given point in space  $\mathbf{F}/q = \mathbf{v} \times \mathbf{B}$ , where  $\mathbf{F}$  is the vector force acting on the particle,  $q$  is the charge on the particle,  $\mathbf{v}$  is the velocity of the particle, and  $\mathbf{B}$  is the magnetic-flux density. Magnetic flux density is expressed in units of tesla (T), (formerly weber per square meter).

**modulation:** The process, or result of the process, whereby some characteristic of a signal waveform is varied in accordance with another wave or signal.

NOTE—For the purpose of this recommended practice, continuous wave (CW) operation is considered to be a special form of modulation, that is, zero modulation.

**near-field region:** A region in the field of an antenna, located near the antenna, in which the electric and magnetic fields do not have a substantially plane-wave character, but vary considerably from point to point. The term *near-field region* is only 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 with 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—For most antennas, the outer boundary of the reactive near-field region is commonly taken to exist at a distance of one-half wavelength from the antenna surface.

**peak pulse amplitude:** The peak value of a pulse excluding those parts considered to be unwanted, such as spikes, provided that the energy is small (5% or less) compared with the total energy at the pulse.

NOTE—Where such excursions are made, it is desirable that the amplitude chosen be illustrated pictorially.

**peak-to-average power ratio:** The ratio between the peak power and the average power of a communication signal. For stochastic signals, the peak power is difficult to define, therefore the 99.9th percentile power level is commonly used as the peak power.

**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.

For a plane-wave incident normally on a planar half-space, the penetration depth  $\delta$  is given by the following equation:

$$\delta = \frac{1}{\omega} \left[ \left( \frac{\mu_0 \epsilon'_r \epsilon_0}{2} \right) \left( \sqrt{1 + \left( \frac{\sigma}{\omega \epsilon'_r \epsilon_0} \right)^2} - 1 \right) \right]^{-1/2} \quad (6)$$

where  $\omega$  is the angular frequency (radians/s),  $\mu_0$  is the free-space permeability ( $4\pi \times 10^{-7}$  H/m),  $\epsilon_0$  is the free space permittivity ( $8.85 \times 10^{-12}$  F/m),  $\epsilon'_r$  is the relative permittivity, and  $\sigma$  is the conductivity of the medium. Penetration depth is expressed in meters (m). The penetration depth is the reciprocal of the medium attenuation constant  $\delta = 1/\alpha$ . A slightly conducting medium is one for which  $\tan\delta \ll 1$ , while a highly conducting medium with  $\tan\delta \gg 1$  is called a good conductor. In a good conductor, the penetration depth is so small that it is called the *skin depth*. The terms *skin depth* and *penetration depth* are used interchangeably for highly conducting media where most of the conduction current concentrates on the surface and very little flows within the conductor.

NOTE—See Equation (6).

**periodic pulse-modulated signal:** A continuous-wave (CW) radio frequency (RF) carrier signal that is pulse-modulated at a known pulse repetition factor with a controlled duty factor.

**permeability ( $\mu$ ):** The ratio of the magnetic flux density to the magnetic field strength at a point. Permeability is expressed in units of henry per meter (H/m).

**permittivity, complex ( $\epsilon$ ):** *See:* **complex permittivity.**

**permittivity, relative ( $\epsilon_r$ ):** *See:* **relative permittivity.**

**pinna (*pl. pinnae*):** The largely cartilaginous projecting portion of the external ear consisting of the helix, lobule, and anti-helix. *Syn:* **auricle.**

**polarization (radiated wave):** That property of a radiated electromagnetic (EM) wave describing the time-varying direction and amplitude of the electric field (E-field) vector; specifically, the figure traced as a function of time by the extremity of the E-field vector at a fixed location in space, as observed along the direction of propagation.

NOTE—In general, the figure is elliptical and it is traced in a clockwise or counterclockwise sense. The commonly referenced circular and linear polarizations are obtained when the ellipse becomes a circle or a straight line, respectively. Clockwise sense rotation of the electric vector is designated right-hand polarization and counterclockwise sense rotation is designated left-hand polarization.

**positioner, probe:** *See:* **probe positioner.**

**power:** A physical quantity describing the rate of delivery or transmission of energy.

NOTE—In this recommended practice power will refer to radio frequency (RF) power expressed in units of watts (W).

**power level:** **(A)** The magnitude of power averaged over a specified interval of time. **(B)** The magnitude of power relative to some arbitrary power chosen as a reference power. **Power level** may be expressed in units in which the power itself is measured or in decibels indicating the ratio to a reference power. **(C)** For handsets with dynamic power control, any of the preset power levels controllable by the base-station.

**predetermination (of standard deviation):** A method in which a larger set of previous readings obtained from the same test conditions is used to estimate the population standard deviation.

**probability distributions:** **(A) Normal:** A probability distribution function that can be described by the following equation:

$$f(X) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{x^2}{2\sigma^2}\right) \quad (7)$$

where  $\sigma$  is defined as the standard deviation. **(B) Rectangular:** A distribution where all values in a continuum are equally likely. **(C) Triangular:** A distribution where the values tend to be clustered near the

center of a continuum. **(D) U-shaped:** A distribution where the values tend to be clustered near the ends of a continuum.

NOTE—See Equation (7).

**probe isotropy:** Pertaining to the degree to which the response of an electric field (E-field) or magnetic field probe is independent of the polarization and direction of propagation of the incident wave.

**probe positioner:** A mechanical device that can be programmed to move the probe under automatic control.

**probe-tip diameter:** The maximum physical dimension of the dielectric encapsulation of the probe assembly measured across the location of the tip of the electric field (E-field) probe.

**pulse repetition frequency (PRF):** In a pulse-modulated RF system using recurrent pulses, the number of pulses per unit of time. The unit of pulse repetition frequency is hertz (Hz).

**pulse repetition rate:** See: **pulse repetition frequency.**

**push-to-talk (radio):** A two-way radio technology in which a mechanical switch is used to trigger between radio transmission and reception. Sometimes called *simplex operation*.

NOTE—Only push-to-talk devices operated at the side of the head are within the scope of this recommended practice.

**reactive field:** Electric and magnetic fields surrounding an antenna or other electromagnetic (EM) devices that result in storage rather than propagation of EM energy.

**readout electronics:** Electronic apparatus for acquiring the probe output signal and converting it to a signal that can be processed by the measurement system or analysis apparatus.

**relative permittivity ( $\epsilon_r$ ):** The ratio of the complex permittivity to the permittivity of free space. The complex relative permittivity,  $\epsilon_r = \epsilon/\epsilon_0$ , of an isotropic, linear lossy dielectric medium is given by the following equation:

$$\epsilon_r = \epsilon'_r - j\epsilon''_r = \epsilon'_r - j\frac{\sigma}{\omega\epsilon_0} = \epsilon'_r \left( 1 - j\frac{\epsilon''_r}{\epsilon'_r} \right) = \epsilon'_r (1 - j \tan \delta) \quad (8)$$

where  $\epsilon_0$  is the free-space permittivity ( $8.854 \times 10^{-12}$  F/m),  $\epsilon'_r$  is the relative permittivity or dielectric constant,  $\sigma$  is the conductivity in S/m, and  $\tan \delta$  is the loss tangent.

NOTE—See Equation (8)

**response time:** The time required for a field-measuring instrument to reach some specified percentage of the final value after being placed in the field to be measured.

NOTE—In this recommended practice, 90% of the final value is assumed.

**rms:** See: **root-mean-square value (of a periodic function).**

**root-mean-square value (of a periodic function):** The square root of the average of the square of the function taken throughout one period. Thus, if  $y$  is a periodic function of  $t$ ,

$$Y_{\text{rms}} = \left[ \frac{1}{T} \int_a^{a+T} y^2 dt \right]^{1/2} \quad (9)$$

where  $Y_{\text{rms}}$  is the rms value of  $y$ ,  $a$  is any value of time, and  $T$  is the period.

NOTE—See Equation (9).

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

**sensitivity:** For a measuring device, the ratio of the magnitude of the measurement instrument response (e.g., voltage) to the magnitude of the quantity measured [e.g., electric field (E-field) strength squared].

**skin depth:** *See: penetration depth.*

**specific absorption rate (SAR):** The 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 ( $\rho$ ), as shown in the following equation:

$$SAR = \frac{d}{dt} \left( \frac{dW}{dm} \right) = \frac{d}{dt} \left( \frac{dW}{\rho dV} \right) \quad (10)$$

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

NOTE 1—See Equation (10).

NOTE 2—Some literature, e.g., Pokovic [B173], refers to a so-called *volume SAR*, expressed in units of mW/cm<sup>3</sup>, where mass density has been set to unity.

NOTE 3—SAR is related to the E-field at a point by the following equation:

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

where

$\sigma$  = conductivity of the tissue (S/m)  
 $\rho$  = mass density of the tissue (kg/m<sup>3</sup>)  
 $E$  = rms E-field strength (V/m)

NOTE 4—SAR is related to the increase in temperature at a point by the following equation:

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

where

$\Delta T$  = change in temperature (°C)  
 $\Delta t$  = duration of exposure (s)  
 $c$  = specific heat capacity (J/kg °C)

This assumes that measurements are made under “ideal” non-thermodynamic circumstances, i.e., no heat loss by thermal diffusion, heat radiation, or thermoregulation (blood flow, sweating, etc.).

**specific absorption rate—peak spatial-average:** The maximum average SAR within a local region based on a specific averaging volume or mass, e.g., any 1 g or 10 g of tissue in the shape of a cube. SAR is expressed in W/kg or equivalently mW/g.

**specific heat:** The ratio of the quantity of heat required to raise the temperature of a unit mass of a substance 1 °C to the heat required to raise the temperature of an equal amount of water by 1 °C.

**specific heat capacity:** The amount of heat necessary to raise the temperature of a unit mass of a substance 1 °C. Specific heat capacity is expressed in units of J/kg K or J/kg °C.

**standing wave:** A spatially periodic or repeating field pattern of amplitude maxima and minima that is generated by two equal-wavelength propagating waves traveling in different directions. For any component of the field, the ratio of the amplitude at one point to that at any other point does not vary with time.

**transmission mode:** The communications protocol or standard that is used to communicate with another terminal or network.

NOTE—Modern terminals may have multiple operating modes incorporated and these may operate individually or multiple modes may be simultaneously active. Examples of operating modes include GSM, EDGE, EVDO, GPRS, CDMA, WCDMA, LTE™, Bluetooth®, Wi-Fi™, and others.<sup>16</sup> Each of these modes may have one or more operating bands associated with it.

**uncertainty (combined):** The estimated standard deviation of the measurement result obtained by combining the individual standard uncertainties of both Type A and Type B evaluations using the usual “root-sum-squares” method of combining standard deviations that are obtained by taking the positive square root of the estimated variances.

**uncertainty (expanded):** A quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand.

NOTE—For well-established measurement procedures and a sufficient number of observations in any Type A evaluations, use of a coverage factor of  $k = 2$  means the expanded uncertainty will provide an interval with a level of confidence close to 95%.

**uncertainty (general):** The estimated amount by which the observed (measured) or calculated value of a quantity may depart from the true value. This is ordinarily taken as the sum of the random errors at the 95% confidence level and the estimated upper limit of the systematic error.

NOTE—The uncertainty is often expressed as the *average deviation*, the *probable error*, or the *standard deviation*.

**uncertainty (phantom):** SAR measurement uncertainty introduced by the deviation of a phantom model from that required by the test procedure, including the dielectric properties of the tissue-equivalent liquids. The deviations may be quantified in terms of the physical shape, size, dimensions of a phantom, and dielectric properties.

**uncertainty (source):** SAR measurement uncertainties due to variations of operating parameters such as drift of output power, operating frequency, signal modulation, antenna operating positions, and other device performance tolerances that could introduce variations in the measured SAR.

**uncertainty (standard):** The estimated standard deviation of a measurement result, equal to the positive square root of the estimated variance.

**uncertainty evaluation (Type A):** The evaluation of uncertainty by the statistical analysis of series of observations (measurements).

**uncertainty evaluation (Type B):** The evaluation of uncertainty by means other than the statistical analysis of series of observations (measurements).

<sup>16</sup> LTE is a trademark of the European Telecommunications Standards Institute. Bluetooth is a registered trademark of the Bluetooth Special Interest Group. Wi-Fi is a trademark of the Wi-Fi Alliance. This information is given for the convenience of users of this standard and does not constitute an endorsement by the IEEE of these products. Equivalent products may be used if they can be shown to lead to the same results.

**voxel:** A volume element of a geometric mesh used when a problem space is discretized to facilitate the use of numerical computations, such as the finite-difference time-domain (FDTD) method, for solving electromagnetic (EM) problems.

**waveguide:** An enclosed system capable of guiding electromagnetic (EM) waves from one place to another. Usually it consists of a metallic tube that is hollow or filled with a homogeneous dielectric material.

### 3.2 Special terms

**confidence interval:** An  $N\%$  confidence interval for a parameter  $X$  means that the results of repeated measurements of  $X$  made in the same way would provide an interval that includes  $X$  for  $N\%$  of the time.  
*Syn:* **confidence level; level of confidence.**

**conservative estimate:** Conservative estimate means an estimate of the peak spatial-average SAR that is equal to or greater than that which would be expected to occur in the heads of a significant majority of persons during the intended use of handheld wireless devices. Conservative estimate does not mean the absolute maximum SAR value that could possibly occur under every conceivable combination of head size, head shape, handset orientation, and spacing relative to the head.

**equivalent current density:** The spatial distribution of RF current densities that are produced by the handset. This distribution produces an approximation of the spatial distribution of magnetic fields (H-fields) induced in the head by an actual handset. The distribution and magnitude of the equivalent current density does not necessarily correspond to the actual current density on the handset.

**field scanning:** Measurement of the electric fields (E-fields) by means of the controlled movement of a probe throughout a prescribed area or volume.

**handheld:** A radio transceiver specifically designed to be operated next to the side of the head while holding it with one hand.

**heterogeneous head model:** An anthropomorphic model of the human head based on MRI images consisting of multiple anatomical structures. Each structure is composed of the appropriate tissue types, such as skin, skull (bone), muscle, brain, or eye tissue. This is in contrast to the *homogeneous head model*, which is also anthropomorphically based but does not contain internal structures or different tissue types.  
*See also:* **phantom.**

**phantom:** A physical model similar in appearance to the human anatomy and comprised of material with electrical properties similar to the corresponding tissues. A phantom representing the human head could be a simple spherical model or a more complex multi-tissue anthropomorphic model. *See also:* **heterogeneous head model.** *Syn:* **mannequin.**

NOTE—The **phantom** could also be a cylindrical (rectangular, circular, elliptical, etc.) container with a flat bottom wall, e.g., for purposes of system check and system validation.

**phantom material:** A material having the equivalent dielectric properties, i.e., permittivity and conductivity, as the tissue it represents.

**probe:** A minimally perturbing device used for measuring components of an RF field in a medium. A probe contains the following components:

- a) An electrically small (in the medium) sensor (or sensors) for detecting the RF field component of interest,
- b) A means for converting the RF signal to a proportional dc or slowly-varying ac signal,
- c) A balanced high-impedance resistive transmission line to extract the rectified signal.

*See also:* **electric field (E-field) probe** in 3.1.

**sagittal (plane):** The median plane of the head, i.e., a plane that divides the left from the right half of the head.

**system check:** The confirmation of the measurement accuracy of the SAR system for testing an individual device, to verify system performance is within the acceptable range specified by the manufacturer. *Syn:* **system verification.**

**system validation:** The verification of the performance specifications of the entire SAR measurement system by testing the system against known values or against other systems.

**uncertainty (assessment):** Assessment uncertainty is related to the assessment of peak spatial-average SAR value for a given SAR distribution using a given setup configuration, e.g., a specific head phantom. This type of uncertainty may include measurement and calibration tolerances in the instrumentation, uncertainties in algorithms used to process the measured data, and other equipment-related variations.

NOTE—Typical benchmark or system validation tests only address measurement related uncertainties. Device performance and production tolerances are not considered in assessment uncertainties.

## 4. Electric field probe and readout electronics

### 4.1 Introduction

This clause describes the instrumentation for the assessment of local SAR in shell phantoms filled with tissue-equivalent liquid using electric field (E-field) measurements.<sup>17</sup> Deviations from ideal performance of E-field probes and associated electronics and their effect on the uncertainty of the peak spatial-average SAR assessment are described. Procedures for E-field probe calibration in tissue-equivalent liquids and calibration uncertainty assessment are described and explained in detail in Annex A.

Miniature E-field probes equipped with three orthogonal diode-loaded dipole sensors are currently employed in dosimetric systems designed for measuring the local SAR of low-power devices to satisfy compliance and other requirements. Since the scope of this recommended practice is limited to evaluating low-power wireless handsets, discussions of E-field probe requirements and characteristics are limited to miniature E-field probes. However, most of the descriptions of E-field probe techniques may also apply for measurements using other types of E-field sensors in other measurement applications. The characteristics of typical E-field probes are described, for example, in Bassen and Smith [B9], Kanda [B117], Schmid et al. [B182], Spectrum Sciences Institute [B186], Strickland and Audeh [B187], and Stuchly et al. [B189]. Other types of E-field sensors have been and are being investigated for use in SAR measurements, e.g., electro-optical devices. While these may have satisfactory sensitivity and spatial resolution, at present none are commercially available with performance comparable to the diode-type E-field probes.

### 4.2 E-field probe requirements

In the near field of a wireless handset, the EM field distributions may have sharp spatial variations in both magnitude and polarization. Thus, the ideal field probe for measuring SAR shall be much smaller than the wavelength in a tissue-equivalent liquid, be isotropic, exhibit a linear response to the square of the incident E-field strength, and shall be transparent (nonperturbing) to the measured field. In practice, the E-field probes consist of a set of three mutually orthogonal center-fed short dipole antennas that are spatially offset from the probe axis. The E-field vector magnitude is the root sum square (RSS) of the three orthogonal components measured by the sensors, as shown in Equation (11):

<sup>17</sup> The rationale and the frequency dependence of the dielectric parameters of tissue-equivalent liquids are described in Clause 5.

$$|E| = \sqrt{|E_1|^2 + |E_2|^2 + |E_3|^2} \quad (11)$$

Each sensor of the probe consists of the following components: an electrically short dipole antenna, a diode detector at the dipole feed point, a dielectric mechanical support, and a highly resistive, RF-transparent, differential transmission line (feed-line) to transmit the signal detected by the diode while maintaining the RF-transparency of the line (see Figure 1). For small RF signals, an ideal detector diode operates in the square-law region providing a rectified output voltage that is proportional to the corresponding square of the rms E-field component. The probe itself consists of three such sensors and has three output ports, each one providing a low-frequency dc-equivalent voltage resulting from the filtering performed by the resistive feed-line, which acts as a distributed R-C low-pass filter for the rectified sensor outputs. The magnitude of the E-field is shown in Equation (12):

$$|E| = \sqrt{\frac{V_1}{\gamma_1} + \frac{V_2}{\gamma_2} + \frac{V_3}{\gamma_3}} \quad (12)$$

where  $V_i$  is the open circuit voltage and  $\gamma_i$  in  $\mu\text{V}/(\text{V}/\text{m})^2$  is the sensitivity at port  $i$ , ( $i = 1, 2, 3$ ). A dielectric cover (typically a cylindrical low-loss plastic sleeve) encloses the probe for chemical and mechanical protection. Figure 2 shows E-field probe relevant features.

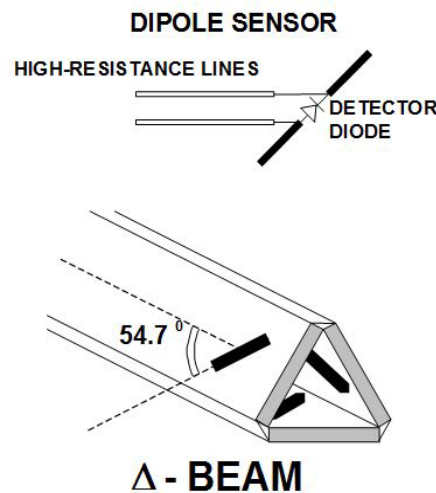
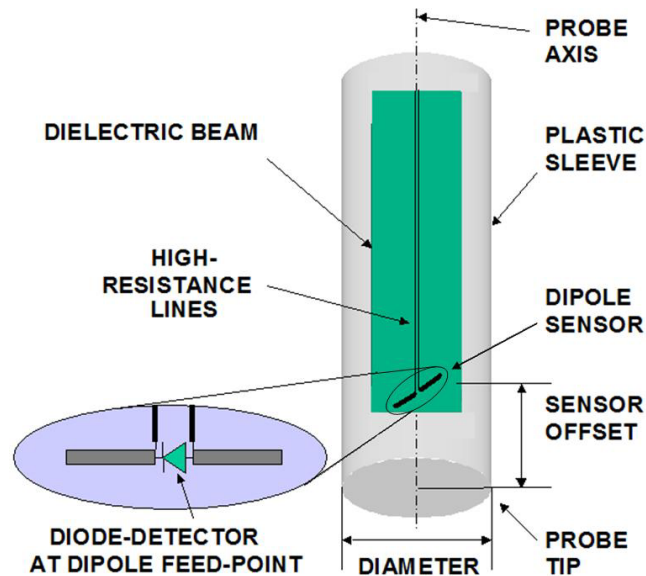


**Figure 1—Typical E-field probe construction. A “Δ-beam” (or “triangular-beam”) dielectric structure supports the three miniature and mutually orthogonal sensor dipoles (Faraone et al. [B66])**

The response of probes designed for SAR measurement may deviate from the ideal requirements. The probe construction materials, the finite size, and the physical displacement among the dipoles as well as manufacturing tolerances influence the field coupling to the sensors. Various factors can produce deviations from an ideal linear response, including non-ideal diode behavior, loading effects, and field pickup by the resistive lines, as well as other spurious coupling. As a consequence, the probe output depends not only on the local field strength but also on other factors that are related to the source or the measurement setup including the following:

- Field polarization and direction of incidence
- Local field gradients at the vicinity of a measurement point where the sensors are located

- c) Media dielectric properties and media boundaries in the vicinity of the probe
- d) Frequency, modulation, and power level of the source
- e) Interfering field sources, e.g., noise, static fields, extremely low-frequency (ELF) fields, from the ambient and nearby equipment
- f) Other physical influences, e.g., temperature, that could change probe performance



NOTE—Sensor offset is measured from the geometric center of the sensors to the tip of the probe enclosure. Sensor displacement is measured from the dipole feed points to the geometric center of the sensors at the probe axis (Faraone et al. [B66]).

**Figure 2—E-field probe features**

The sensitivity of the probe output to these factors shall be known in order to determine the probe-related calibration and measurement uncertainty. Deviations between the measurement and calibration configurations and conditions will increase the measurement uncertainty. Calibration shall be preceded by a complete characterization of the probe independently of the measurement system, in order to evaluate the probe response to these factors. It will also be necessary to calibrate the probe in different tissue-equivalent liquids because of different probe responses in frequency-dependent tissue-equivalent media. Each calibration shall indicate the range of parameters (permittivity, conductivity, frequency, temperature) and signal characteristics for which the assessed probe uncertainty is valid. Some of the preceding influences can be partially compensated in the output measurement system with techniques such as filtering, frequency compensation, and diode response linearization (Pokovic [B173]). The effects of other influences can usually be reduced by following ad hoc measurement procedures, e.g., repeated measurements, or aligning the probe's sensors with the E-field vector (IEEE Std 1309-2005). However, these techniques are typically not required for measuring the SAR of handsets; therefore, they are not described.

Because of the high-resistance lines and the use of unbiased detector diodes, the typical source impedances of miniaturized E-field probes are around several megohms (MΩ). The output voltage at the probe connector is dependent on the input impedance and biasing conditions of the instrumentation amplifier in the readout electronics, which could influence the probe sensitivity, dynamic response, and voltage offset errors.

The probe shall be calibrated together with the specific type of readout electronics and post-processing system used during measurements. If a probe uses different types of readout electronics allowed by the

SAR system, differences in input characteristics between a probe and the different types of readout electronics shall be considered and included in the uncertainty evaluation. The combination of probe and readout electronics shall be verified through system validation. The readout electronics shall also be calibrated (see 4.3). If the probe is used with different SAR measurement systems, the probe output performance shall also be evaluated without the processing and compensation subsystems, so that the probe characteristics are known explicitly. Furthermore, the minimum requirements for the readout electronics input circuits shall be specified. In the following subclauses, the E-field probe characteristics and possible uncertainty sources are described. Mechanisms that produce coupling of ambient external fields to the probe's sensors under different measurement conditions as well as means for evaluating the error and criteria for estimating the calibration uncertainty are discussed. Test procedures for evaluating the characteristics of the probe and estimating calibration uncertainties associated with each characteristic are provided in Annex A. Finally, two different probe calibration techniques, temperature-transfer and waveguide methods, are discussed and the specific procedures are explained in Annex A.

#### 4.2.1 E-field probe isotropy, isotropy errors, and evaluation procedures

Isotropy is a desired characteristic of an E-field probe that allows it to respond equally to incident fields independently of the direction of incidence and polarization.

- a) Two components of isotropy can be defined as follows:
  - 1) *Axial isotropy*, which is the ability of a probe to respond equally to a transverse electromagnetic (TEM) plane wave impinging from a direction along the probe axis, as described in Figure 3.
  - 2) *Hemispherical isotropy*, which is the ability of a probe to respond equally to TEM plane waves impinging with arbitrary polarization from directions around the surface of a hemisphere, as described in Figure 3. Evaluation of hemispherical isotropy accounts for evaluation of axial isotropy as well.
- b) Deviation from the ideal isotropic response results from a number of causes including the following:
  - 1) Probe construction variations from the ideal design configuration
  - 2) Unequal responses of the individual sensors, e.g., diode sensitivity
  - 3) Asymmetric field perturbation due to asymmetric construction of the probe enclosure or mechanical supports of the sensors
  - 4) Displacement of the sensors from the probe axis
  - 5) Signal pickup by the feed-lines, which may depend on the incidence angle and polarization of the impinging field

The dielectric properties of the surrounding media have a strong influence on the field deflection at the probe boundary, and therefore, the probe isotropy shall be assessed within a specific dielectric medium of intended use.

- c) Depending on the setup being used, this is accomplished by performing E-field measurements while carrying out some or all of the following steps:
  - 1) Rotate the probe around its longitudinal "axis"
  - 2) Rotate the field propagation direction from parallel to the probe axis (frontal incident) to normal to the probe axis (lateral incident)
  - 3) Rotate the E-field polarization from normal to parallel to the incidence plane formed by the probe axis and the field propagation direction (this definition breaks down when the incidence direction is along the probe axis; in that case, probe rotation replaces field polarization rotation)

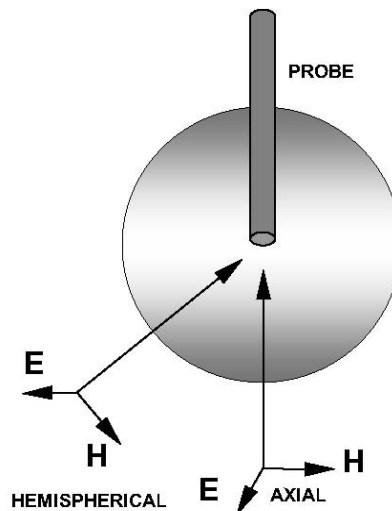


**Figure 3—Schematic representation of axial and hemispheric probe isotropy**

The isotropy assessment procedures are described in detail in A.5. The isotropy shall be characterized for at least one frequency in each frequency band of interest. The isotropy uncertainty is the maximum deviation of the measured SAR with respect to the average SAR over all measurements defined by the test protocol with an assumed rectangular error distribution.

Due to the high conductivity of liquid-filled phantoms, the E-field polarization at the field maximum is predominantly parallel to the phantom surface. The probe inclination angles for the isotropy assessment shall cover at least the range of angles specified in Table 6. If the angles are limited to a narrower range during routine measurements, the isotropy assessment may be performed only in that range. When the isotropy uncertainty is assessed within a limited range, it shall be indicated in the field-probe calibration and SAR measurement documentation along with a description of the probe positioning system.

#### 4.2.2 Spatial resolution

Spatial resolution of a probe identifies its ability to discriminate between two SAR peaks in close proximity. The SAR uncertainty associated with the spatial resolution of the probe is the deviation in the measured spatial SAR from the actual value (e.g., determined by numerical simulations or measurement using a probe with a smaller diameter). In near-field exposure conditions, the separation between these peaks may be an electrically short distance since the SAR is strongly related to the surface current density on the radiating device and its proximity to the body. Also, geometrical and electrical features of the radiating structures within a transmitter can cause the SAR peaks to be closer than a probe tip diameter.

Due to the physical construction of a probe, the output is not related to the local field strength at a point but depends on the field in the volume surrounding the sensors, i.e., the probe output corresponds to the field integrated over a finite volume according to the geometric configurations of the sensors within the probe. This averaging process can result in lower measured values at local field maxima and higher values at field minima. In addition, sensor displacement from the probe axis produces a shift of the measurement location for each sensor from the geometric center where the calibration is defined.

The effect of the probe spatial resolution on the 1 g and 10 g peak spatial-average SAR is negligible for probes with diameters no greater than 8 mm in the frequency range 300 MHz to 2000 MHz (Faraone [B66]) and one third of a wavelength in the medium in the frequency range 2 GHz to 6 GHz (as described in Table 1). Therefore, dosimetric E-field probes with an external plastic sleeve diameter at the probe tip no larger than these values are required for all tests described in this recommended practice.

One of the following two test setups shall be used for assessing the spatial resolution of E-field probes:

- a) A balanced quadrupole is used to generate two electrically close SAR peaks. The quadrupole has two pairs of equipotential poles excited with equal magnitude and opposite phase signals. Between the pairs there is enough clearance (typically 10 mm) to insert the probe tip. SAR is measured with the probe moving through the SAR peaks between the opposite potential pairs along a horizontal line flush with the open termination of the quadrupole (see Figure A.6).
- b) Two parallel dipoles are used, separated by 10 mm, both touching the bottom outer surface of a flat phantom with a 2 mm shell thickness. The dipoles are fed with equal magnitude and opposite phase signals. The probe is placed in the phantom close to the mixture-phantom interface and moved along the line passing directly above the dipole feed points (see Figure A.7) at a fixed height from the phantom surface to minimize probe boundary effect error (i.e., 5 mm, as shown in Figure A.7). Two distinct SAR peaks with a null in between should be encountered.

Test procedures for assessing the spatial resolution of E-field probes are given in A.6.

#### 4.2.3 Probe tip outer dimensions and sensor offset

In general, dosimetric probes are constructed and protected using materials (low loss and low dielectric constant parameters) that substantially differ from the tissue-equivalent liquid (high loss and high dielectric constant material). This produces local distortion of the field due to scattered fields, which can produce exaggerated field readings near the liquid and phantom interface. In order to keep the distortion small (and to maintain good spatial resolution), the probe tip diameter shall be small with respect to a wavelength in media. This will avoid resonance issues and minimize the influence of the field characteristics due to probe boundary effects. In general, the effect of the disturbances is reduced with smaller probe tips. The probe tip diameter shall be within one-third of a wavelength in the medium, as shown in Table 1. At frequencies at or below 2 GHz, the maximum probe tip diameter is 8 mm.

The E-field distribution in the lossy medium is a function of skin depth,  $\delta$ , and incident magnetic field (H-field) distribution, i.e., the field can attenuate even faster than the skin depth with respect to the normal distance from the phantom boundary. Due to this strong attenuation, extrapolation becomes very sensitive to uncertainties of the measured points, i.e., local field distortions, boundary effects, noise, etc. In order to keep the uncertainties within reasonable boundaries, the closest measurement point M1 (see Figure 18) shall be measured at a distance within  $z_{50\%} = \delta \ln(2)/2$  (where  $\ln(2) \approx 0.693$  is the natural logarithm of 2) where the SAR is more than 50% of the SAR at the surface. These distances are provided in column 7 of Table 1, assuming plane wave attenuation. However, the attenuation is typically stronger for RF sources close to the phantom surface than it is for plane waves (Douglas and Chou [B58]), especially at lower frequencies such that the minimal distance up to 3 GHz is defined as  $z_{M1} = 5$  mm (Table 6 and column 8 of Table 1). However, at frequencies above 3 GHz,  $z_{M1}$  is set to a maximum of  $z_{50\%}$  (Table 1, column 8), as the skin depth is similar to that of a plane wave at higher frequencies (Douglas and Chou [B59]). The distance  $z_{M1}$  corresponds to the sensor offset plus the minimal probe tip distance to the phantom surface. As accurate results cannot be measured when the probe is in direct contact with the phantom, the probe tip diameter, sensor offset, and probe tip to phantom surface distance shall satisfy the requirements of this recommended practice.

**Table 1—Probe requirements as a function of frequency and liquid parameters**

| 1            | 2                                                      | 3                                            | 4                                                    | 5                                                | 6                                     | 7                                                                          | 8                                                  |
|--------------|--------------------------------------------------------|----------------------------------------------|------------------------------------------------------|--------------------------------------------------|---------------------------------------|----------------------------------------------------------------------------|----------------------------------------------------|
| $f$<br>(MHz) | Medium<br>relative<br>permittivity<br>( $\epsilon_r$ ) | Medium<br>conductivity ( $\sigma$ )<br>(S/m) | Wavelength<br>in the<br>medium ( $\lambda$ )<br>(mm) | Plane wave<br>skin depth<br>( $\delta$ )<br>(mm) | Max.<br>probe tip<br>diameter<br>(mm) | 50%<br>distance<br>for M1<br>[ $z_{50\%} =$<br>$\delta \ln(2)/2$ ]<br>(mm) | Max.<br>distance<br>for M1<br>( $z_{M1}$ )<br>(mm) |
| 300          | 45.3                                                   | 0.87                                         | 148.6                                                | 46.1                                             | 8                                     | 16.0                                                                       | 5                                                  |
| 450          | 43.5                                                   | 0.87                                         | 101.1                                                | 42.9                                             | 8                                     | 14.9                                                                       | 5                                                  |
| 750          | 41.9                                                   | 0.89                                         | 61.8                                                 | 39.8                                             | 8                                     | 13.8                                                                       | 5                                                  |
| 835          | 41.5                                                   | 0.90                                         | 55.8                                                 | 38.9                                             | 8                                     | 13.5                                                                       | 5                                                  |
| 900          | 41.5                                                   | 0.97                                         | 51.7                                                 | 36.1                                             | 8                                     | 12.5                                                                       | 5                                                  |
| 1450         | 40.5                                                   | 1.20                                         | 32.5                                                 | 28.6                                             | 8                                     | 9.9                                                                        | 5                                                  |
| 1500         | 40.4                                                   | 1.23                                         | 31.5                                                 | 27.9                                             | 8                                     | 9.7                                                                        | 5                                                  |
| 1640         | 40.2                                                   | 1.31                                         | 28.9                                                 | 26.1                                             | 8                                     | 9.0                                                                        | 5                                                  |
| 1750         | 40.1                                                   | 1.37                                         | 27.1                                                 | 24.9                                             | 8                                     | 8.6                                                                        | 5                                                  |
| 1800         | 40.0                                                   | 1.40                                         | 26.4                                                 | 24.3                                             | 8                                     | 8.4                                                                        | 5                                                  |
| 1900         | 40.0                                                   | 1.40                                         | 25.0                                                 | 24.3                                             | 8                                     | 8.4                                                                        | 5                                                  |
| 2000         | 40.0                                                   | 1.40                                         | 23.7                                                 | 24.2                                             | 8                                     | 8.4                                                                        | 5                                                  |
| 2100         | 39.8                                                   | 1.49                                         | 22.6                                                 | 22.8                                             | 7.5                                   | 7.9                                                                        | 5                                                  |
| 2300         | 39.5                                                   | 1.67                                         | 20.8                                                 | 20.2                                             | 6.9                                   | 7.0                                                                        | 5                                                  |
| 2450         | 39.2                                                   | 1.80                                         | 19.6                                                 | 18.7                                             | 6.5                                   | 6.5                                                                        | 5                                                  |
| 2600         | 39.0                                                   | 1.96                                         | 18.5                                                 | 17.2                                             | 6.2                                   | 5.9                                                                        | 5                                                  |
| 3000         | 38.5                                                   | 2.40                                         | 16.1                                                 | 13.9                                             | 5.4                                   | 4.8                                                                        | 5                                                  |
| 4000         | 37.4                                                   | 3.43                                         | 12.3                                                 | 9.6                                              | 4.1                                   | 3.3                                                                        | 3.3                                                |
| 5000         | 36.2                                                   | 4.45                                         | 10.0                                                 | 7.3                                              | 3.3                                   | 2.5                                                                        | 2.5                                                |
| 5200         | 36                                                     | 4.66                                         | 9.6                                                  | 7.0                                              | 3.2                                   | 2.4                                                                        | 2.4                                                |
| 5400         | 35.8                                                   | 4.86                                         | 9.3                                                  | 6.7                                              | 3.1                                   | 2.3                                                                        | 2.3                                                |
| 5600         | 35.5                                                   | 5.07                                         | 9.0                                                  | 6.4                                              | 3.0                                   | 2.2                                                                        | 2.2                                                |
| 5800         | 35.3                                                   | 5.27                                         | 8.7                                                  | 6.1                                              | 2.9                                   | 2.1                                                                        | 2.1                                                |
| 6000         | 35.1                                                   | 5.48                                         | 8.4                                                  | 5.9                                              | 2.8                                   | 2.0                                                                        | 2.0                                                |

#### 4.2.4 Boundary effects

Boundary effects arise when the tip of an E-field probe approaches the interface between two dielectric media at tissue-equivalent liquid and phantom shell boundary. Under these conditions, the external field is strongly perturbed by the superposition of a scattered field. The effect of the boundary on the measured SAR depends on the probe dimensions and materials and the measurement procedures used in the system including the following:

- Distance from the probe tip to the phantom surface and media interface
- The angle and orientation of the probe with respect to the phantom surface
- Extrapolation algorithm used for determining the SAR at the surface of the phantom
- Frequency, field gradients, and field decay in the medium, at the measurement location
- Averaging volume (1 g or 10 g)
- Optional implementation of compensation routines for reducing the boundary effects

Setups for assessing the boundary effect are described in A.8. One consists of a rectangular waveguide filled with head tissue-equivalent liquid that is separated from the air-filled portion of the waveguide with

an impedance-matching dielectric slab (Pokovic [B173]); see Table A.1 for permittivity requirements. For frequencies below 800 MHz, the system validation setup of 8.3 should be employed.

Computer simulations and measurements show that in shell phantoms filled with tissue-equivalent liquids at frequencies below 3 GHz, the error in measured SAR values due to boundary effects is typically less than 2% when the distance between the probe tip and the phantom surface is greater than one probe tip diameter. At frequencies above 3 GHz, the boundary effect is larger. The boundary effect is typically less than 2% if the distance is larger than the probe tip diameter multiplied by  $f/3$  GHz (e.g., distance larger than two probe tip diameters at 6 GHz). For shorter distances, the boundary effect produces a strong increase in the probe sensitivity, up to 50% when the probe enclosure is in flat contact with the phantom surface. Errors can be reduced if the probe tip is kept at least one probe tip diameter from the phantom surface. However, this is not always possible for larger diameter probe tips and must be avoided, given that the probe sensors shall be sufficiently close to the phantom shell for accurate extrapolation of the zoom scan measurements (see 6.5.2). For the flat phantom and dipole configuration, the boundary effects can be evaluated by comparison with the response of a probe having a smaller tip diameter (e.g., Pokovic et al. [B175] uses a single sensor probe) or by comparison with analytical solutions or numerical simulations (numerical solutions are acceptable only when the results are validated against measurements at points sufficiently far from the boundary that boundary effects are neglected).

### 4.3 Characteristics of the probe readout electronics

The probe output is processed by the readout electronics and associated instrumentation that combine the voltages from the probe's sensors to provide an output that is proportional to the amplitude-squared of the E-field incident on the sensors. Detector diodes at the dipole feed point are used to rectify the sensor voltages. The rectified signals are transmitted through resistive (RF-transparent) lines to the readout electronics system. For a continuous-wave signal at low field strength levels, the probe output is proportional to the square of the amplitude of the incident E-field; at higher signal levels (above the diode compression point), the output is not linearly proportional to  $|E|^2$ , but becomes proportional to  $|E|$ . This signal compression will lead to an underestimation of the actual SAR at high field strength conditions if it is not compensated correctly through probe calibration. Also the amplifiers can deviate from an ideal linear response and introduce additional uncertainty.

For offset errors associated with the probe readout electronics, see 4.5.

### 4.4 Probe linearity

The diode compression has to be compensated with a linearization algorithm applied to each detector signal before any further evaluation. Calibration of the probe at different power levels may not be sufficient, since the total error depends on how the field is distributed and varies among the three sensors. For example, the same field polarization would produce a different reading if detected by one sensor alone compared with detection among all the sensors. The non-linearity is not only dependent on field strength but also on modulation characteristics. Since the resistive lines and the amplifier capacitance act as a low-pass filter with cutoff frequencies typically between 10 Hz and 1 kHz (video bandwidth), the modulation envelope of the signal is attenuated by the high-impedance lines before reaching the amplifier input. If the system measures a time-averaged signal that is below the diode compression level, a modulated signal with high peak-to-average power ratio could still be above this level for a substantial fraction of the measurement time. Algorithms shall be employed to compensate for the diode compression.<sup>18</sup> It is therefore crucial to characterize the non-linearity of the probe and linearize the probe response properly.

<sup>18</sup> Due to filtering by the high impedance lines of the probe, the modulation envelope cannot be reproduced at the amplifier input, a priori information regarding the duty factor shall be incorporated in the linearization algorithm for TDMA signals. For CDMA (IS-95) signals, with random noise-like modulations and higher peak-to-average power ratios (~2.5 dB), the same linearization parameters used for CW signals may be employed (Di Nallo and Faraone [B54]) with less than 3% to 5% overestimation error at typical handset power levels (~250 mW). Larger errors are possible for similar or other wireless technologies with larger peak-to-average power ratios (see A.1 and A.2 for further information and calibration procedures that reduce these errors). This issue will be further explored in future revisions.

The “peak detector effect” inherent in diode detectors is another nonlinear effect that exists for amplitude modulated signals. For high power pulsed signals, the nonlinear diode impedance can change the probe from an average to a peak detector by charging the capacitance of the probe leads and amplifier with little or no discharging. An increase in the resistive-line impedance can minimize the peak detector effect by reducing the dependence of the signal timing characteristics on the variable source impedance of the diode (Pokovic [B173]) and amplifier input time constant.

#### 4.5 Offset errors in probe and readout electronics

The probe design and readout electronics can introduce errors that translate to an offset voltage at the probe output. The sensor lines shall not be metallic (highly conductive) and shall not be grounded so as to avoid reflections from metal surfaces within the phantom liquid (see 5.1). Offset errors include the following:

- a) Offset errors only association with the probe
  - 1) Thermal noise associated with the diode resistance and high resistance lines of the probe (1  $\mu\text{V}$  to 3  $\mu\text{V}$  peak-to-peak from 0.1 Hz to 10 Hz)
  - 2) Photovoltaic effects in the detector diodes in transparent probe tips (several  $\mu\text{V}$ )
  - 3) Voltages generated by impurities in the resistive lines and connections (0 to 100  $\mu\text{V}$ )
  - 4) Static charges built up by moving the probe in the tissue-equivalent liquid (up to 1  $\mu\text{V}$ )
  - 5) ELF signal pickup in the lines that is rectified by the sensor diodes
- b) Offset errors associated with the electronics independent of the probe
  - 1) Thermal noise associated with the input impedance
  - 2) Offset voltage of the input amplifiers; if offset zeroing is not provided, the offset drift with time and temperature may become unacceptable
  - 3) Direct pickup and rectification of RF signals from the ambient or device under test, at the amplifier inputs
- c) Offset errors of the readout electronics with the probe
  - 1) Offset bias currents flowing from the amplifier input through the high resistance probe lines
  - 2) Rectification of ambient high-frequency RF signals caused by nonlinearities at the input stage of the amplifiers
  - 3) Common-mode signals on the probe lines converted into differential mode due to limited common-mode rejection of the input amplifiers or asymmetries in the input circuitry
  - 4) Common-mode signals on the probe transmission lines that are generated by the following:
    - Low-frequency conducted pickup from power lines or the probe positioner motors
    - Ground potential differences between the measurement system and the source (ground loops)
    - Conducted interference induced on the a/c power lines of the SAR measurement system

Many of these offset contributions depend strongly on the actual system setup and environment and when they combine it is often difficult to identify each individual contribution or predict the offset in a specific environment. Therefore, the offset shall be assessed in the actual measurement system configuration with all components in use and without the RF fields or power from the test device (RF source). While the rectified signal is always unipolar, the offset can be bipolar.

Procedures for the related uncertainty evaluations (probe linearity and detection limit) are described in E.2.4 for CW signals and E.2.5 for modulated signals. Deviations from the ideal response of diode detectors are determined during probe calibration and are compensated during measurements with respect to the signal and modulation characteristics used for the measured wireless technology. The probe measurement uncertainty assessment shall be performed with the processing and compensation routines included.

## 4.6 Probe calibration

The response of the probe's sensors depends on the dielectric parameters of the surrounding media and the signal frequency. The probe shall therefore be calibrated in media having dielectric properties that are equivalent to the mixtures that will be used for the tissue-equivalent liquids at the operational frequencies of the wireless devices being tested. Since the measurement of the media properties also involves some uncertainty, the sensitivity of the probe calibration with respect to the media parameters shall be assessed, e.g., by calibrating the probe in different tissue-equivalent liquids exhibiting differences in the dielectric parameters. The differences in the dielectric parameters are due to the tolerances at the test frequency ( $\pm 10\%$ ), and the parameter change at different frequencies across the valid frequency range of the probe calibration. A sensitivity factor shall be determined that accounts for these differences. The sensitivity factor shall be documented. Sensitivity factors that account for these differences are described in E.3.2. Dielectric parameter compensation (see E.3.2) shall not be applied to probe calibration. The calibration uncertainty can be reduced when the calibration setup is similar to the typical measurement situation and when the probe isotropy errors are reduced during calibration by means of redundant measurements, e.g., by rotating the probe.

Since the calibration is carried out in the target tissue in a field with gradients similar to those expected from the test device, the location of the calibration point with respect to the probe, i.e., probe tip and sensor centers, should be indicated. Any uncertainty in probe positioning increases the calibration uncertainty.

The field strength in the calibration setup shall be accurately determined and documented. This is done by the following:

- a) SAR assessment by temperature measurements (known as the *transfer method* because calibration is transferred from temperature to E-field). See A.3.2.1.
- b) Input RF power measurements leading to analytical field values at the calibration point under specific experimental conditions, e.g., rectangular waveguide. See A.3.2.2.
- c) Measurements with calibrated field probes

Since the input characteristics of the probe readout electronics influence the signal at the probe output, they shall be reported in the probe calibration report. The probe calibration is only valid when used with probe readout electronics having the same input characteristics. The probe readout electronics shall be calibrated as well [input characteristics, amplification, analog-to-digital (A/D) conversion, etc.]. It is recommended that the probe be calibrated together with the same type of readout electronics used for the measurement system. Otherwise, additional probe calibration and measurement errors shall be specified (see A.9).

The calibration fields in lossy media are gradient fields. Since the field can vary over the probe-tip region, the exact location of the calibration center (nominal field point) of the probe shall be indicated. The nominal field point shall be the geometrical center of the sensor dipoles, where the feed points are located; otherwise, the reading will be incorrect when the probe is used in fields with different gradients. The position of the calibration center is used later in the extrapolation algorithm to determine the SAR at the phantom shell/liquid interface. The probe calibration uncertainty consists of the uncertainty in the actual and measured field strength in the calibration setup, including tissue dielectric parameters, and the probe positioning uncertainty during calibration. Two calibration procedures, based on rate of temperature increase and waveguide calibration techniques, are presented in A.3.

#### 4.6.1 Probe calibration procedures

For frequencies above 800 MHz, where rectangular waveguide dimensions are more practical (see Table A.1), calibration in waveguide is recommended. This calibration setup consists of an appropriate size rectangular waveguide with its axis of propagation oriented vertically ( $z$ -direction). A dielectric separation slab allows the tissue-equivalent liquid to be filled from the top and provides electrical match from the empty waveguide section to the dielectric-filled section. The transverse field distribution in the liquid corresponds to the fundamental mode ( $TE_{10}$ ) with an exponential decay in the vertical direction ( $z$ -axis). The liquid level shall be deep enough such that reflections from the top liquid surface do not affect the calibration field. The SAR in the liquid can be determined from the waveguide dimensions, measurements of the forward and reflected power and the measured decay in the liquid. The exact equations are given in A.3. The field is measured at a point along the vertical center axis of the waveguide. The analytical field at the nominal measurement point (i.e., geometric center of the probe sensors) is used to calibrate the sensors.

For frequencies below 800 MHz, temperature transfer calibration should be performed when the waveguide size becomes relatively large and unavailable (see Footnote a of Table 2). The setup for this calibration may consist of a flat phantom with a dipole source, or a coaxial calorimeter system, such as that described in Loader et al. [B141]. The field is measured with the probe under calibration at the reference position in the liquid. This location is the nominal field point corresponding to the geometric center of the probe's sensors. The actual SAR in the liquid is assessed with a temperature probe positioned at the same nominal field points. The rate of temperature increase of the liquid is assessed during short exposure periods, before thermal diffusion takes effect, starting from thermal equilibrium. The specific heat capacity of the liquid is measured with calorimeters. The calibration E-field is calculated from the temperature increase and the specific heat capacity and conductivity of the liquid.

Table 2 summarizes the probe calibration procedures.

**Table 2—Probe calibration procedures**

|                     |                                    |
|---------------------|------------------------------------|
| Frequency < 800 MHz | Thermal calibration <sup>a</sup>   |
| Frequency ≥ 800 MHz | Waveguide calibration <sup>b</sup> |

<sup>a</sup> If large calibration waveguides are available, waveguide calibration is preferable.

<sup>b</sup> Calibration waveguides are preferred, but thermal calibration may be used.

##### 4.6.1.1 Validity range of probe calibration

The probe is calibrated in a specific tissue-equivalent liquid and at a specific frequency. The calibration parameters so derived are rigorously valid only at that frequency and for those particular tissue parameters. However, due to the short electrical length of the sensor dipoles, the calibration factors are usually frequency insensitive, i.e., they change very slowly with the RF signal frequency. Moreover, the dependence of such calibration factors with frequency is often slow and predictable. For this reason, it is acceptable to define limited frequency and liquid parameter ranges within which the calibration factors are applicable. In particular, it is important that information be provided on the calibration certificate to substantiate the calibration validity range, frequency, dielectric parameters, and associated uncertainties. Additionally, the measurement uncertainty due to the deviations in frequency and dielectric parameters shall be assessed, as described in E.2.1.

##### 4.6.1.2 Calibration environment

The ambient conditions defined in Table 7 shall be maintained during probe calibration.

#### 4.6.2 Traceability of the probe calibration

All instrumentation used for probe calibrations, e.g., RF generators, power meters, voltmeters, temperature sensors, and the equipment used to characterize tissue parameters, shall be within the calibration accuracy range recommended by the manufacturer or other site compliance requirements. Documentation shall be available showing that instrumentation calibrations are traceable to national or international metrology institutions, e.g., the National Institute of Standards and Technology (NIST) in the US, National Physical Laboratory (NPL) in the UK.

## 5. Phantom models

### 5.1 Introduction

In order to evaluate the near-field exposure produced by wireless handsets, phantom models simulating the human head have been used. These models vary from simplified (Spectrum Sciences Institute [B185]; Wojcik and Cardinal [B202]), to more human-like (“anthropomorphic”) models (Balzano et al. [B5]; Hombach et al. [B95]; Kuster and Balzano [B128]; Wang and Fujiwara [B198]; Yu et al. [B205]). In addition to the different sizes and shapes of the phantom models, various manufacturers and test laboratories used different dielectric properties for the tissue-equivalent liquids and different handset test positions prior to the publication of IEEE Std 1528-2003. In the absence of standardized tissue property parameters and device test positions, the test results from different laboratories for the same wireless handset can vary due to different test configurations. When test results approach the applicable SAR limits, additional error margins are often needed to verify that the test results are reliable. To reduce measurement variations, a phantom model with a standardized size and shape has been defined in this recommended practice, as well as specific parameters for the tissue-equivalent liquids, so that all laboratories can assess SAR using the same standardized model. The variation that results when different laboratories make SAR measurements using the same phantom and procedures has been evaluated (Davis et al. [B48], Balzano et al. [B7]; Davis and Balzano [B47]). To minimize reflections from the upper surface of the tissue-equivalent liquid, the depth of the liquid should be at least 15 cm, which is approximately the distance between the ears of a typical human head. Liquid depth of less than 15 cm may be used if it is demonstrated (e.g., using numerical simulations) that the effect of reflections on peak spatial-average SAR values is less than 1% under worst-case conditions. If it is more than 1% but less than 3%, the worst-case value shall be added to the uncertainty budget. The use of the Specific Anthropomorphic Mannequin (SAM) phantom and handset test positions in standardized measurement procedures will reduce lab-to-lab variability. The selection of tissue conductivities and the choice of a large head size and a thin ear spacer were considered to provide a conservative estimate of the peak spatial-average SAR associated with the operating configurations expected by typical wireless handset users, as discussed in 1.4.

### 5.2 Phantom head models: requirements

#### 5.2.1 General

In order to assess the SAR associated with the near-field exposure conditions encountered under intended use conditions of a wireless handset, i.e., with handset held against the ear, the phantom model should resemble the head of a typical user. For wireless handsets intended for operation while held next to the body, a flat phantom should be used. The scope of this recommended practice is limited to wireless handsets operated while held next to the ear with energy coupling confined to the head region, so the phantom model is limited to a head and neck, truncated above the shoulders. Results in Iskander et al. [B102] showed that SAR in a heterogeneous head might be affected by the shoulders. Their model used a

worst-case vertical position with the bottom of the handset almost touching the elevated flat shoulder and with the handset placed at distances up to 15 cm from the head. These positions are unrealistic compared with the positions specified in Clause 6 where the handset touches the ear and the bottom of the handset is near the mouth, relatively far from the shoulder. That reference also concluded that an isolated model of the head and neck produced accurate SAR values independent of the shoulder when the device was held at 0.5 cm from the head. Therefore shoulder effects are expected to be negligible for the conditions specified in this recommended practice.

The test methods described in this standard are focused on sagittally bisected phantoms oriented horizontally. For the typical setup of a sagittally bisected phantom, each half of the head model is placed on its side, and the device under test (DUT) is placed underneath. Other phantom configurations that satisfy the requirements of this standard may be used; however, different measurement procedures that are not covered by this standard may be necessary.

## 5.2.2 Head model considerations—shape and dimensions

The relative distances between the tissue-equivalent liquid and the various parts of a handset that carry RF current may have a strong influence on the local SAR. These distances depend on the head shape and the pinna representation. Results from Schönborn et al. [B183] have shown that SAR values are expected to be slightly more conservative if a phantom representing a large adult head is used, because the currents induced by magnetic field coupling are greater. A larger head with a larger radius of curvature is closer to a flat structure with the tissue boundary closer to the RF current source, thereby capturing more energy than a smaller head. Numerically computed SAR results in Gandhi et al. [B83] showed a higher peak spatial-average SAR in a smaller child's head, which was obtained by proportionally scaling down an adult head. One interpretation of Gandhi's results is that the higher SAR in the smaller head was due to mainly the smaller ear spacing of the scaled child's head model (Schönborn et al. [B183]). The thin ear spacer adopted in this recommended practice is intended to provide a conservative method for estimating SAR in both large and small heads. Recent results in Lee and Pack [B133], Lee et al. [B134], and Watanabe et al. [B201] also show that large head models provide conservative SAR estimates.

Since a larger head is expected to result in higher SAR due to the larger curvature radius (which provides better RF coupling between the head and the RF current source), for a constant pinna thickness (Schönborn et al. [B183]) a large male head with a low-loss spacer to simulate a compressed pinna represents a conservative head exposure for men, women, and children. The phantom model described in 5.4 is intended to allow assessment of the peak spatial-average SAR that would occur among a reasonably large user group when the device is positioned in the configurations specified in this recommended practice. Additional discussion about the rationale of selecting the shape and dimensions of the SAM phantom is given in 1.4.

To reduce SAR variations from the phantom and to support uniform test procedures, standard size, shape, and dimensions of the head phantom have been established for repeatable fabrication from a computer-aided design (CAD) file. Thickness and tolerances of the phantom shell are specified so that manufacturing tolerances have a minimal effect on measured SAR. Phantom tolerances shall be confirmed by the manufacturer and declared with a production certificate.

## 5.2.3 Homogeneous versus heterogeneous head models

The dependence of the peak spatial-average SAR on the physical implementation of head models was analyzed in Kuster et al. [B131] and has shown that small dependencies on the internal heterogeneous anatomy are feasible. Both heterogeneous and homogenous head models have been developed for assessing the SAR associated with the use of handheld two-way radios or radio transceivers used for personal communications. For example, SAR measurements using such models and E-field probes have been reported in Balzano et al. [B5] and Cleveland and Athey [B40]. Heterogeneous head models with multiple tissues, including skin, skull, muscle, brain, and eyes are difficult to construct. Moreover, measurements are

often limited to specific regions of the phantom because of restrictions imposed by the bony structure. As shown in Gandhi et al. [B83], Hombach et al. [B95], Meier et al. [B146], Beard et al. [B10], and Christ et al. [B35] measurements in homogenous head models at 900 MHz and 1800 MHz can overestimate or underestimate SAR depending on the dielectric properties of the tissue-equivalent liquid used (see also 1.4.1.5). A conservative approach for assessing SAR can be achieved by choosing suitable tissue dielectric parameters, which provide some overestimation when used in a homogeneous phantom. Head models that contain a homogeneous liquid inside a thin low-loss dielectric shell allow an E-field probe to search for regions of peak SAR using a multi-axis probe positioner. Currently, manufacturers and test laboratories are using liquid-filled homogeneous head models for testing wireless handsets because of difficulties in making measurements in and constructing heterogeneous head models.

## 5.2.4 The external ear (pinna)

Since the SAR produced by a wireless handset depends strongly on the separation distances and positioning defined by the handset and the user's head, specific test positions shall be established between the handset and the phantom so that the SAR is not underestimated. For wireless handsets placed in the intended use position, the handset is held such that the earpiece makes physical contact with the pinna. Since the pinna is in direct contact with the handset, the head model and the positioning of the handset can affect RF energy absorption in the pinna and the head. Without the pinna to provide physical separation on a head model, the antenna and associated radiating structures of a wireless handset would be placed much closer to the head, which could lead to higher than expected head SAR levels.

Numerical calculations show that for some handset models, the peak spatial-average SAR induced in the pinna could be higher than the corresponding maximum value induced inside the head. This is due to the very close proximity of the pinna to the RF source (handset) (Burkhardt and Kuster [B25]; Gandhi and Lazzi [B82]; Gandhi et al. [B83]; Watanabe et al. [B199]; Beard et al. [B10]). IEEE SCC34 (now ICES TC34) performed an extensive analysis of the topic for IEEE Std 1528-2003. The following basic issues were addressed:

- a) How the phantom ear could be constructed to enable measurements to be made in the head so that a conservative estimate of the peak spatial-average SAR in the head would be maintained without introducing higher measurement uncertainties.
- b) Whether the peak spatial-average SAR in the pinna should be measured, and whether such measurements could be made accurately.
- c) The pinna model that should be used with the SAM phantom in order to produce a realistic, conservative measurement of the peak spatial-average SAR inside the head of the model (excluding the SAR in the pinna, which is outside of the head).
- d) Whether a "lossless" pinna model should be used instead of a "lossy" pinna so that head SAR remains conservative. A lossless model of the pinna can be made using the same low-loss dielectric material as the head model shell. A lossy pinna can be formed by an indentation simulating the shape of the human pinna on the inner surface of the head phantom. This indentation is then filled with simulated head tissue-equivalent liquid used for the head.

The following published results were considered when IEEE Std 1528-2003 was developed:

- Watanabe et al. [B199] showed that a lossless ear model could cause the peak SAR inside the head to shift from directly beneath the pinna to the cheek region. They suggested using a lossy pinna.
- Yu et al. [B205] used a head model with an indentation at the phantom inner surface to simulate the pinna and suggested that this model could be used for SAR testing. This idea was considered, but it was noted that such a model is inconsistent with the real anatomy of the pinna, which has an air cavity in the external ear.

- Based on numerical modeling results, Gandhi and Lazzi [B82] found that a lossy pinna had a significant effect on the maximum peak spatial-average SAR inside the head. They recommended the inclusion of a lossy pinna.
- Balzano et al. [B5] used a thin low-loss dielectric spacer in a physical head model to represent the pinna. Wojcik and Cardinal [B203] suggest that a 6 mm lossless spacer in the form of a wedge is a good representation. This recommendation was based on their detailed analysis of the ear related to handset shapes, usage, and auditory considerations. This ear model is 6 mm thick, consisting of a low-loss 4 mm thick spacer added to the 2 mm thick phantom shell to represent the much larger (28.8 mm) gap at the back of the ear specified in the head data described by Gordon et al. [B84].
- Kanda et al. [B119] measured the effects of a lossy versus a lossless model of the pinna on a flat phantom at 835 MHz. The phantom contained head tissue-equivalent liquid with a 6 cm × 3.2 cm × 0.2 cm rectangular trough placed outside the flat phantom shell, to simulate the pinna. Various shapes of openings in the shell of the phantom were used to connect the pinna with the tissue-equivalent liquid in the head region. Using a dipole source, measurements indicated that the presence of tissue-equivalent material in the pinna region did not enhance RF energy absorption inside the head region of the phantom. Accordingly the authors recommended use of a lossless ear.
- Christ et al. [B33], [B36] computed the SAR in the pinna using numerical methods. They used a model of the human head derived from MRI data, including the actual pinna. Comparisons were made of the peak spatial-average SAR inside the MRI-based head model with lossy pinna versus the peak spatial-average SAR in the SAM head model (an earlier version) developed for this recommended practice with a lossless pinna at frequencies of 900 MHz and 1800 MHz. Christ et al. [B33] concluded that the maximum peak spatial-average SAR in the tissue-equivalent liquid of the head model with the lossless pinna provides a conservative overestimate of the SAR measured in the head. The pinna shape and thickness recommendations stated in another work from that group (Burkhardt and Kuster [B25]) pertain to a lossy anatomically accurate pinna derived from MRI scans are not applicable to the pinna model selected in this recommended practice.

IEEE SCC34 (now ICES TC34) also studied the feasibility of measuring SAR inside a model of a lossy pinna. When the pinna of a head phantom consists of a trough filled with a liquid tissue-equivalent liquid, and an irregularly shaped opening interconnects the liquids of the pinna and the head, the experimental results will be highly dependent on the positioning of the probe during SAR averaging. The results will also be influenced by the physical shape (rounding) of the interconnecting shells and by the boundary effects of this complex structure when using even the smallest available E-field probe. Because of these measurement limitations, larger measurement uncertainties are expected for a complex-shaped pinna partially filled with lossy material. SAR measurements in ear models were determined to be impractical using present technology, and further research and development is needed before reliable complex pinna models can be adopted.

Therefore, for purposes of this recommended practice, a thin, solid, low-loss dielectric spacer shaped like a human ear shall be used to model the pinna. This spacer does not have detailed ridges like an actual human pinna, which enables the handset to be located properly with respect to the tissue boundary and with good repeatability. Using the resulting homogenous head model with a thin, lossless ear spacer, it is expected that the SAR in the head of a significant majority of users is not underestimated.

The preceding analysis was conducted for IEEE Std 1528-2003, having an applicable frequency range of 300 MHz to 3000 MHz. For this standard, having an expanded frequency range of 300 MHz to 6000 MHz, ICES TC34 has postulated that the same general conclusions leading to the choice of a low-loss dielectric spacer model for the pinna continue to apply for head SAR measurements. The issue of whether the SAM phantom, including the existing pinna, leads to a conservative SAR estimate for head and pinna is being investigated by ICES TC34, as explained in 1.4.1.5.

### 5.2.5 Hand and device holder considerations

During normal operation, the head and hand are in the near-field of the handset used next to the ear and hence both absorb energy. For extremities including the hand, a higher SAR limit is allowed, i.e., 4 W/kg averaged over 10 g of tissue in IEEE Std C95.1-2005 and ICNIRP Guidelines. Numerical and experimental studies have shown that the SAR in the hand at the power levels used by handsets is not expected to exceed those limits (Francavilla et al. [B71]; Gandhi et al. [B83]; Jensen and Rahmat-Samii [B110], [B111]; Kuster et al. [B131]; Watanabe et al. [B200]).<sup>19</sup> Furthermore, a practical phantom for SAR measurement in the hand is unavailable. Therefore, SAR measurement in the hand is not addressed in this standard.

The influence of a hand holding a handset on the head SAR measurements was considered in IEEE Std 1528-2003. Earlier work by Balzano et al. [B5] and Kuster et al. [B131] reported that the presence of the hand either decreases or has no significant effect on the head SAR, although numerical results by Meyer et al. in 2001 [B151] showed a case featuring 7% increase in head SAR due to the hand. These deviations in head SAR were concluded to be within the conservativeness provided by the SAM phantom. Based on these studies, the exclusion of the hand from test procedures appeared to lead to head SAR overestimation in a majority of situations, as confirmed by more recent research results on mobile phone SAR levels. For these reasons, hand models are not considered in this recommended practice.

The state of dosimetric research on the effect of the hand on head SAR produced by mobile phones is illustrated in D.4. This research shows that there are cases when the SAR produced by mobile phones in the SAM phantom may increase as well as decrease significantly due to the hand holding the handset, for specific operating bands and hand grips. These initial findings have not shown that the SAM phantom may underestimate in a statistically significant measure the SAR in real users when the hand is not present during SAR tests. Nevertheless they deserve further investigations, which may potentially warrant future changes in this recommended practice.

For the methods described in this recommended practice, the handset is positioned against the head phantom using a device holder fabricated from low-loss dielectric (with relative permittivity,  $\epsilon'_r$ , less than 5 and loss tangent,  $\tan\delta$ , less than 0.05) to minimize perturbations to handset current density and SAR distributions. To confirm that the SAR test results are not altered by the holder, a substitution test (see E.4.1) is required by replacing the holder with low-density, low-permittivity dielectric blocks, e.g., foamed polystyrene.

## 5.3 Tissue and tissue-equivalent liquid properties

### 5.3.1 Dielectric properties

The dielectric properties of tissues have been extensively studied over the past several decades (Burdette et al. [B24]; Gabriel et al. [B78]; Schwan and Piersol [B184]; Stuchly and Stuchly [B188]). Tissue dielectric parameters are frequency dependent, having permittivities that decrease and conductivities that increase with frequency. Differences in published values for tissue dielectric properties are largely due to different measurement methods, tissue temperatures, tissue aging effects, etc. (Gajsek et al. [B81]). In this recommended practice, all tissue dielectric properties are derived according to the most recent and comprehensive data reported in Gabriel [B75] and Gabriel et al. [B79], [B80]. Phantom materials with the same dielectric properties as tissues have been developed for RF dosimetry studies and medical applications, e.g., Chou et al. [B30]. The adoption and use of standardized tissue-equivalent parameters for phantom materials (liquids) in this recommended practice minimizes one of the major components of SAR measurement uncertainty.

<sup>19</sup> These studies were performed for frequencies below 3 GHz.