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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

IEEE Standards Coordinating Committee 34

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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

Sponsor

**Standards Coordinating Committee 34
(Product Performance Standards Relative to the
Safe Use of Electromagnetic Energy)**

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Abstract: IEEE Std 1528-2003 specifies protocols and test procedures 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–3 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 standard. The results are representative of those expected during conditions of normal 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 standard. The following items are described in detail: measurement concepts, measurement techniques, instruments, calibration techniques, simulated-tissue (phantom) models, including homogeneous anatomical 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 measurement techniques. This standard 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 uncertainty in order to produce valid and repeatable data.

Keywords: cellular and mobile telephones, dosimetry, handheld wireless transceivers, measurement uncertainty, miniature electric field (E-field) probes, nonionizing radiation, RF/microwave exposure assessment, RF/microwave hazard assessment, SAR measurements, SAR measurement systems

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Introduction

(This introduction is not part 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.)

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.^a The title of SCC34 is “Product Performance Standards Relative to the Safe Use of Electromagnetic Energy.” Standards developed by this committee will be expressed in terms of parameters easily measured by product manufacturers, such as output power, voltage, or current, and will provide detailed procedures for measuring and computing parameters more difficult to measure, such as RF/microwave power density, electric and magnetic field strengths, SAR, and induced current density. Standards developed by SCC34 will not specify limits for human exposure to electromagnetic fields, but will refer to established limits found in science-based standards such as IEEE Std C95.1TM-1999, IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz.

Prior to 1995, assessment of exposure to various products was based on the procedures found in IEEE Std C95.3TM-1991, IEEE Recommended Practice for the Measurement of Potentially Hazardous Electromagnetic Fields—RF and Microwave [B71] that addresses exposure assessment in general but does not provide detailed procedures that could be applied to specific products.

In accordance with policies of the IEEE, SCC34 standards will be issued and developed as IEEE standards, as well as being submitted to ANSI for recognition.

The present scope of IEEE SCC34 is: “Development of product performance standards relative to the safe use of electromagnetic energy for products that emit electromagnetic energy by design or as a by-product of their operation at frequencies up to 300 GHz.” The committee will coordinate with other committees whose scopes are contiguous with SCC34.

SCC34 is responsible for this recommended practice. Subcommittee 2 (SC2) of SCC34 was established in February 1997 to develop standard protocols for certifying that certain portable wireless devices, such as handheld radio transceivers, wireless LANs, and similar devices, meet specific SAR criteria. Although the scope of SC2 covers a variety of devices, this recommended practice is devoted exclusively to handsets used for personal wireless communication services.

This recommended practice specifies protocols for the measurement of the peak spatial-average SAR in the head of users of certain handheld radio transceivers that are used for personal wireless communications, operate in the 300 MHz–3 GHz frequency range, and are intended to be operated while held against the ear. Specifically, this recommended practice describes the concepts, measurement techniques, instruments, calibration techniques, phantom models for SAR system validation, and limitations of systems used for measuring the radio frequency (RF) E-field strength for purposes of determining the spatial-peak mass-averaged SAR, e.g., per 1 g or 10 g of tissue, in simulated tissue models, including homogeneous anatomical models of the human head.

This recommended practice is intended to determine a conservative estimate of the peak spatial-average SAR induced in the head of a significant majority of persons^b during conditions of normal use of handheld wireless devices. It is not intended to determine the absolute maximum SAR value possible under every conceivable combination of head size, head shape, handset orientation, and spacing relative to the head. The SAR determined by following the procedures specified in this recommended practice is subject to

^aThe Electromagnetic Energy Association was dissolved in 2000.

^bThe term “significant majority of persons” is used in this recommended practice to refer to any population that can be characterized adequately by the phantom described in Clause 5 and Annex D.

measurement uncertainty and other uncertainties that are discussed in the standard. This recommended practice does not address the measurement of SAR induced in the external tissues of the head, e.g., the external ear (pinna).

This recommended practice is intended primarily for use by engineers and other specialists who are familiar with electromagnetic theory and measurement techniques. This standard, an extension of IEEE Std C95.3-2002, does not recommend specific SAR limit values since these are found in other documents, e.g., IEEE Std C95.1-1999 or the latest International Commission on Non-Ionizing Radiation Protection Guidelines [B69].^c The benefits to the users include standardized and accepted protocols, measurement and validation techniques, and means for estimating the overall uncertainty in order to produce valid and repeatable data. Coordination with European and other international standards developing organizations, e.g., CENELEC Technical Committee 106X and IEC Technical Committee 106, has been achieved on specific issues by common membership on these committees.

Participants

This recommended practice was prepared by Working Group 1 (WG 1, Measurement Techniques) of SC2 (Wireless Handset Certification) of IEEE SCC34. The following persons participated on the working group that developed this recommended practice.

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^cIt 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 IEEE Std C95.1-1999 or the ICNIRP guidelines [B69]. 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

1. Overview

1.1 Scope

The scope of this recommended practice is 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–3 GHz frequency range and provides a conservative estimate¹ of the peak spatial-average SAR representative of that which would be expected to occur in the heads of a significant majority of persons during normal use 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.

This recommended practice does not address the measurement of SAR induced in the external tissues of the head, for example the external ear (pinna). Concepts, measurement techniques, instruments, calibration techniques, phantom models for SAR *system validation*, and limitations of systems used for measuring the radio frequency (RF) electric field strength for purposes of determining the spatial-peak mass-averaged SAR, e.g., per 1 g or 10 g, in simulated-tissue models, including homogeneous anatomical models of the human head are described. A specific anthropomorphic head model, the dielectric properties and formulations for tissue-equivalent phantom materials, and techniques for verifying the dielectric properties of the phantom material are provided. The relative orientations and spacing between the head model and the handset are defined. Procedures are described for calibrating electric field (E-field) probes used for SAR

¹As 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 head size, head shape, handset orientation, and spacing relative to the head (3.16).

measurements and evaluating measurement uncertainties associated with probe characteristics, such as isotropy, linearity, spatial resolution, boundary effects, modulation effects, offset voltage, and environmental conditions. Procedures for assessing system uncertainties associated with calibration, probe positioning, and the dielectric properties of the tissue-equivalent solutions are also included. Detailed suggested procedures are provided in the annexes.

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 users with standardized and accepted protocols and test procedures, measurement and validation techniques, and means for estimating the overall uncertainty in order to produce valid and repeatable data. Specific SAR limit values are not included because these are given in other documents, e.g., IEEE Std C95.1TM-1999.

1.3 Background

Various national regulatory agencies, for example the Federal Communications Commission (FCC) in the US, require the peak spatial-average SAR associated with certain wireless handsets to be evaluated to ensure compliance with their rules (Code of Federal Regulations [B31] and guidelines of the FCC [B45], [B46]).² The SAR values in such rules and guidelines, defined as the rate at which energy is absorbed per unit mass in an object exposed to an RF field, are usually based on standards such as IEEE Std C95.1-1999 or guidelines such as those developed by the International Commission on Non-Ionizing Radiation Protection [B69].

The SAR in a biological body exposed to an 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. [B23]). Since the RF energy induced in the body is scattered and absorbed at various interfaces, the internal field and hence the SAR distribution is nonuniform. Energy coupling is complicated even further by source geometry and mutual coupling when the exposure is in the near field (Stuchly et al. [B138]), e.g., exposures conditions associated with handheld radio transceivers (Balzano et al. [B5]). Kuster and Balzano [B91] have shown that the peak spatial-average SAR values associated with use of wireless handsets are mainly a function of the 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 strength in tissue-equivalent medium using anthropomorphic models of the human head.

The current state-of-the-art regarding SAR compliance 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 electrical properties of the tissue-equivalent liquid as averaged to represent “head” tissue are chosen to ensure that the measured SAR values are conservative, i.e., consistently exhibit a slight overestimation compared with an equivalently shaped heterogeneous head model.

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

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

²The numbers in brackets correspond to those of the bibliography in Annex H.

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

where c is the specific heat capacity, ΔT is the change in temperature, Δt is exposure duration, σ is the electrical conductivity, $|E|$ is the rms magnitude of the electric field strength vector, and ρ is the mass density of the medium. As indicated in Equation (1), the SAR is determined from the initial slope ($t = 0$) of the temperature increase curve. Because the local (not spatially averaged) SAR is given by the energy absorption, $\sigma |E|^2$, divided by the local mass density ρ , the respective SAR values will differ by a constant factor given by the ratio of the density of the human head tissue, ρ_{head} , to the density of the tissue-equivalent liquid, ρ_{liquid} , as shown in Equation (3):

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

For the purposes of this recommended practice, the head tissue density is assumed to be 1000 kg/m³, with corresponding 1 g and 10 g averaging volumes of 1 cm³ and 10 cm³, 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:

$$SAR_{\text{head}} = \frac{\rho_{\text{solution}}}{\rho_{\text{head}}} \underbrace{C_{\text{solution}} \frac{\Delta T}{\Delta t} \bigg|_{t=0}}_{SAR_{\text{liquid}}} \quad (4)$$

This recommended practice addresses the measurement of the peak spatial-average SAR associated with wireless handsets held next to the head and operating at frequencies between 300 MHz and 3 GHz. The relevant characteristics and SAR dynamic range are

- a) Frequency range: 300 MHz–3 GHz
- b) System dynamic range³: 10 mW/kg–100 W/kg
- c) Probe-tip diameter: 8 mm or less
- d) Signal modulation⁴:
 - 1) Unmodulated—continuous wave (CW)
 - 2) Pulsed modulation 10 Hz–1 kHz pulse repetition rates, and duty factors greater than 4%.

For SAR evaluation of low-power wireless handsets using tissue-equivalent liquids representative of high-water content tissues, the typical dynamic range of an E-field probe extends from approximately 3–350 V/m, which corresponds to a range in temperature rise of 3–40 µK/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.

³The dynamic range of 10 mW/kg–100 W/kg allows the assessment of peak spatial-average SAR with a specified measurement uncertainty (see Clause 7) between 0.4–10 W/kg for CW and pulsed signals with duty factors as low as 10%. A system that measures CW at 100 W/kg can only measure 10 W/kg for a signal with 10% or higher duty factor. The lower limit is established by noise for time-averaged SAR in CW. If the system does not have a dynamic range down to 12 mW/kg, the error due to noise at 0.4 W/kg is larger than 3%.

⁴This range of repetition rates includes all digital modulations presently used for mobile communication systems, e.g., TDMA and CDMA.

SAR measurements are carried out by scanning within a thin anatomically based phantom shell filled with a tissue-equivalent liquid along the interior of the phantom shell, 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 below can be used to average the local SAR over a prescribed volume to determine the peak spatial-average SAR (Balzano et al. [B6]; Schmid et al. [B129]; Wojcik and Cardinal [B150]; Yu et al. [B151]).

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. Recommended procedures for calibration and uncertainty assessment are also described.

Clause 5 and Annex D define 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 phantom and device test protocols. The dielectric properties of the phantom material (tissue-equivalent liquid) are given, along with mixing recipes, in Annex C. Methods that can be used to verify dielectric properties are provided in Annex B.

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, 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 meets any applicable SAR limits, 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.

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. Finally, Annex G describes construction details for reference dipoles used in the routine *system check* and *system validation*.

1.4 Rationale

This recommended practice describes test methods that may be used to simulate the exposure of a reasonable cross section of users associated with the operation of certain 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 below. 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 better compared without minor differences between phantoms obscuring agreement or disagreement of 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, each tested on both sides of the head with specific handset operating configurations, are intended to cover a reasonable cross section of normal use conditions.

1.4.1 Specific Anthropomorphic Mannequin (SAM)

The rationale for choosing the specific head model (i.e., SAM) phantom 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 normal use of wireless handsets.
- b) The test results shall not unnecessarily overestimate the peak SAR expected in actual users.
- c) The phantom shall allow stable and repeatable device positioning for peak SAR measurements and be effective for verifying repeatability and reproducibility via interlaboratory comparisons.
- d) The phantom shall be practical for routine compliance testing.
- 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 above criteria, especially item a), i.e., providing a conservative estimate of the actual SAR, is a function of at least the following parameters:

- 1) Head size, shape, and homogeneity of the shell and liquid.
- 2) Electrical parameters of head tissue-equivalent liquid and phantom shell.
- 3) Ear pinna/auricle size, shape, material properties.
- 4) Exclusion of the hand.

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. [B94]). 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 should 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 distance from the phantom to the 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 exclusion of the hand in the test procedure, while not directly a phantom attribute, will in general lead to overestimates of peak spatial-average SAR compared with normal use conditions.

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. Absolute overestimate conditions can never be established for all possible head, device, and positioning configurations. Further discussion is included in Clause 5 and in other places in this recommended practice on how the homogeneous SAM phantom was derived to overestimate peak spatial-average SAR. Validation of the SAM model by Subcommittee 2 (SC2) members and other groups is ongoing, using direct comparison of experimental and numerically calculated peak spatial-average SARs in heterogeneous and homogeneous head phantoms.

In order to ensure that the results are not overly restrictive, and thereby unnecessarily inhibit the advancement of new mobile communications technologies, SAR overestimates should be as small as possible. Overestimates of the order of 20% have been reported (Hombach et al. [B68]; Meier et al. [B103]) and were deemed reasonable. Achieving an optimal compromise between over- or underestimate conditions is a complex task, which is why the conductivity of the tissue-equivalent liquid is not selected to be arbitrarily large, for example.

Several homogeneous phantom shapes were considered by SC2 before selecting SAM, including

- 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, this model may cause considerable changes in antenna loading and impedance due to improper antenna spacing near the skull behind and above the pinna. Spherical phantoms of appropriate diameter better resemble the proper antenna spacing in the head posterior region. However, when compared with the human head, the greater relative spacing below the pinna reference point of a spherical phantom may lead to an underestimation of SAR. Moreover, spherical shapes have other repeatability and volume scanning challenges. Therefore, SC2 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, to allow uniform reproduction and manufacture by multiple vendors. Based on committee consensus, available knowledge, and experience, after extensive deliberations and design iterations, the present, final version of the SAM phantom was adopted.

1.4.1.1 Head size

Results presented in Hombach et al. [B68], Kuster and Balzano [B91], and Schönborn and Kuster [B130] 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 results in overall smaller distances between the handset and the tissue boundary will provide more conservative results because the separation between the equivalent current densities on the device under test 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. [B94]). 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. [B59]). 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 [B91], 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 compliance testing with scanned E-field probes, the head must be simulated as a homogeneous liquid, rather than as a multilayered or high-density solid. To fulfill the conservative criteria in SAR assessment, the homogeneous liquid parameters must 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 described in Clause 5 are based on a study of the anatomical variations in the head region behind and above the ear for a cross section of a representative user population (Drossos et al. [B38]). 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 determined to produce the same (or slightly higher) peak spatial-average SAR values compared to the highest values occurring in the heterogeneous cases.

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.

An anthropomorphic pinna orientation with respect to the head will better simulate normal use conditions, and the peak spatial-average SAR assessment will be less sensitive 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. 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.

SC2 reviewed results from several investigations of various pinna shapes and compositions (see 5.1.4). 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 19–28 mm spacing between the rear edge of the pinna (when not compressed) and the head shown in the anthropometric data, thereby contributing to the conservative conditions of SAM for SAR assessments.

1.4.1.5 Phantom validation

The phantom validation process involves comparison of numerically modeled SAR in heterogeneous and homogeneous phantoms, followed by validation of the homogeneous numerical models by measurements in homogeneous phantoms. Because the intent is a relative comparison of the various head representations, the validation process uses simplified handset and source type models, rather than high-resolution, exactly detailed handset models. Correlation between the current distributions of the simplified handset models and actual detailed handsets is not relevant to the anatomical comparisons, and is beyond the scope of this recommended practice. In order to validate the SAM phantom and ensure 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 a highly detailed heterogeneous computer model and the SAR induced in a computer model of the SAM phantom.

In earlier studies, SAR evaluations were performed for several canonical antenna or source types and heterogeneous magnetic resonance imaging (MRI)-based head models. The antenna types include quarter-wave ($\lambda/4$ -wave) monopoles, half-wave ($\lambda/2$ -wave) dipoles (Dimbylow [B35]; Dimbylow and Mann [B36]; Watanabe et al. [B147]), and other lengths (Gandhi et al. [B58]) 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 (PIFA) antennas mounted on the rear or side of a handset box, have also been investigated. These studies cannot be utilized for SAM validation, however, since the test conditions are not comparable and the corresponding SAR values for SAM are not available.

Only the results of more recent studies directly comparing 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. [B27] with different generic handsets either equipped with helical and $\lambda/4$ -wave monopole antennas operating at frequencies of 900 MHz and 1800 MHz and placed in the touch 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^3). 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. [B27] by shifting the handset box with wire or helical monopoles along the B-M line of SAM (Clause 5) towards the mouth. The SAR overestimates shown in Christ et al. [B27] ranged from 5% to over 150%. A more recent study has confirmed these results using a model of a commercially available handset (Chavannes et al. [B21]). These studies at 900 MHz and 1800 MHz were used to validate the conservative characteristics of SAM, and therefore the concepts and criteria from which the SAM phantom was derived. Since the same rationale is considered to be applicable in the 300 MHz–3 GHz frequency range, it is expected that SAM provides conservative SAR values over that entire frequency range.

1.4.2 Test positions

The criteria used by SC2 to select a range of handset test positions were:

- a) The number of test positions shall be a minimum for representing normal use conditions and configurations.
- b) The positions shall appropriately reflect the operational conditions and normal use positioning of the handset next to the head 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 repeatability of SAR measurements and be describable and usable to verify repeatability and reproducibility via future interlaboratory comparisons.

Because of the almost infinite number of possible positions in which a handset could be used and therefore tested, SC2 compromised with two positions per side. The positions selected are the intended or normal use position and the tilt position. One of these two positions is expected to represent well the maximum exposure when the device is used as intended. This may not be representative of a “worst-case” position, which may be outside of the range of normal use positions and difficult to determine within a reasonably finite number of tests.

Because variations in position may cause significant variations in peak spatial-average SAR, the protocol should ensure that the handset is tested for the expected variations of the intended use position. Based on available information and experience, SC2 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 normal 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 normal use positions and difficult to determine within a reasonably finite number of tests.

1.4.2.1 General dependence of exposure on position

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. Basically, RF currents on the metal or conductive parts of the handset, e.g., the device case or the antenna, induce currents in the body. Since the handset case is in contact with the face in the cheek or “touch” 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 peak equivalent current density in regions above the acoustic output, including external antennas (Kuster [B90]).

1.4.2.2 Rationale for the two specified positions

The cheek or touch 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 repeatability. It further reflects the most conservative condition for exposure associated with peak equivalent current densities on the device case. The tilt position was defined on the basis of SC2 reviews of various handset usage surveys. For most flat handsets, the tilt position corresponds approximately to the “100°” position of CENELEC ES 59005:1998 [B19].

From 1997 through 2001, various test labs and SC2 members evaluated a large number of devices in accordance with CENELEC ES 59005:1998 [B19] recommendations. The ES 59005 recommendations use four positions: cheek, (touch), “intended,” “100°,” and “tilted (90°/30° tilted).” An analysis of compliance tests on 50 devices (Kuster [B89]; Kuster et al. [B94]) showed that the maximum SAR occurred in only two cases in the “intended” or “tilted” positions, where maximum means greater than 10% of the value obtained in the touch 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. [B94]), 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), SC2 concluded that the four positions per side defined in CENELEC ES 59005:1998 [B19] could be reduced to two positions per side without affecting the requirement for a conservative assessment of user exposure (Kuster [B90]).

2. References

This recommended practice should be used in conjunction with the following standards. When the following standards are superseded by an approved revision, the revision shall apply.

IEEE Std 1309™-1996, IEEE Standard for Calibration of Electromagnetic Field Sensors and Probes, Excluding Antennas, from 9 kHz to 40 GHz.^{5,6}

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

⁵The IEEE standards or products referred to in Clause 2 are trademarks of the Institute of Electrical and Electronics Engineers, Incorporated.

⁶IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

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–300 GHz.

3. Definitions

For the purposes of this recommended practice, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition [B70], should be referenced for terms not defined in this clause.

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

3.2 antenna: That part of a transmitting or receiving system that is designed to radiate or to receive EM waves.

3.3 antenna driving point: That part of the radiating structure where the RF currents start to support the 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.

3.4 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.

3.5 anthropometric: Referring to comparative measurements of the human body relative to specified populations.

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

3.7 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.

3.8 average power($\bar{P}$): The time-averaged rate of energy transfer

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

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).

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

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

3.11 body-mount (or body-worn) radio: A wireless transceiver that is normally operated (intended use) by means of acoustic or electrical control accessories while the device is placed in the pocket of a garment or is maintained close to the body by means of a belt clip, holster, pouch, lanyard, or similar device.

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

NOTE—This can be a major source of error. Computer simulations and measurements show that in shell phantoms filled with tissue simulating 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 half the probe diameter.

3.13 confidence interval: For purposes of this recommended practice, 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.**

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

3.15 conductivity (σ): A factor such that the conduction-current density is equal to the electric field strength in the material multiplied by the conductivity. Conductivity is expressed in units of siemens per meter (S/m).

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

3.16 conservative estimate: For purposes of this recommended practice, conservative estimate means an estimate of the peak spatial-average SAR, including uncertainties as defined in this standard, representative of that which would be expected to occur in the heads of a significant majority of persons during normal 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.

3.17 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, $k \times$ (combined uncertainty) = (expanded uncertainty). When $k = 1$, $P \sim 0.68$; $k = 2$, $P \sim 0.95$; $k = 3$, $P \sim 0.999$.

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

3.19 dielectric constant: See: **permittivity.**

3.20 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.

3.21 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, a half-wavelength long, so energized that the current has a node only at each end.

3.22 dispatch radio: A radio technology for permitting a maximum number of terminal devices to have access to the same two-way radio communication circuit.

3.23 duty cycle: *See: duty factor.*

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

3.25 duty ratio: The ratio of average-to-peak envelope power.

3.26 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.

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

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

3.28 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 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 an “I”-beam, (or “H”-beam) or a “Δ” (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.

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

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.

3.30 electric 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. Electric field strength is expressed in units of volt per meter (V/m).

3.31 electric flux density (displacement): A vector equal to the product of the electric 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^2).

3.32 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, it is distance in wavelengths multiplied by 2π to give radians, or by 360 to give degrees.

3.33 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.

3.34 energy density (EM field): The EM field energy contained in a given infinitesimal volume divided by that volume. Energy density is expressed in units of joule per cubic meter (J/m^3).

NOTES

1—The term energy density may be used with modifiers, such as instantaneous, maximum, and peak.

2—In speaking of average energy density in general, it is necessary to distinguish between the space-average (at a given instant) and the time-average (at a given point).

3.35 equivalent current density: For purposes of this recommended practice, the spatial distribution of RF current densities that are external to the model of a head. 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.

3.36 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 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.

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

3.38 field scanning: For purposes of this recommended practice, sampling of the electric or magnetic fields by means of the controlled movement of a probe throughout a prescribed volume.

3.39 finite-difference time-domain (FDTD) method: A numerical algorithm for solving Maxwell's differential equations of 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.

3.40 frontal plane: The plane that cuts the body into anterior (front) and posterior (rear) halves when a person is standing.

3.41 handheld: For purposes of this recommended practice, a portable radio transceiver specifically designed to be operated next to the side of the head while holding it with one hand.

3.42 handset: A handheld device consisting of an earphone and a microphone intended to be operated close to the side of the head and acoustically coupled to the ear. For purposes of this recommended practice, an assembly to be held in the hand of the user that includes a radio transmitter and receiver. *See: handheld.*

3.43 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.*

3.44 heterogeneous head model: For purposes of this recommended practice, an anthropomorphic model of the human head based on MRI images and constructed or modeled with multiple structures. Each structure is composed of the appropriate single, simulated-tissue type, 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, upright.*

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

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

3.47 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).

3.48 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. *See also:* **normal use position.**

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

3.49 intrinsic impedance (of free space): The ratio of the electric field strength to the magnetic field strength of a propagating EM wave. Intrinsic impedance is specified in units of ohms (Ω). The intrinsic impedance of a plane wave in free space is $\cong 120\pi \Omega$ – approximately 377Ω .

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

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

3.52 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 μ , i.e., $H = B/\mu$.

3.53 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.

3.54 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).

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

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

3.56 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.

3.57 normal use position: During use, the position and orientation of the handset in accordance with the instructions provided by the manufacturer. *See also:* **intended use.**

3.58 peak power output: (A) General: For a modulated carrier system, the output power averaged over a carrier cycle, at the maximum amplitude that can occur with any combination of signals to be transmitted.
(B) Pulse-modulated carrier system: The root-mean-square (rms) value of rectangular pulse of RF power. The peak power of a periodic pulse train is equal to the ratio of the average power to the duty factor. Peak power is expressed in units of watts.

3.59 peak pulse amplitude: The maximum absolute 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.

3.60 penetration depth: For a given frequency, the depth at which the electric 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 on a planar surface, the penetration depth δ is given by

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

where ω is the angular frequency (radians/s), μ is the free-space permeability ($4\pi \times 10^{-7}$ H/m), ϵ_0 is the free-space permittivity (8.85×10^{-12} F/m), ϵ'_r is the relative permittivity, and σ 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.

3.61 permittivity, complex (ϵ): The ratio of the electric flux density in a medium to the electric field strength at a point. The permittivity of biological tissues is frequency dependent. Permittivity may be a complex quantity and it is expressed in units of farad per meter (F/m).

3.62 permittivity, relative (ϵ_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

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

where ϵ_0 is the free-space permittivity (8.854×10^{-12} F/m), ϵ'_r is the relative permittivity or dielectric constant, σ is the conductivity in S/m, and $\tan \delta$ is the loss tangent.

NOTE—For purposes of this standard, the convention $E^{j\omega t}$ is used to describe time-varying E-fields.

3.63 permeability (μ): 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).

3.64 phantom: For purposes of this recommended practice, a representation or model usually 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**.

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*.

3.65 phantom, upright: A symmetric full-head (left and right halves) phantom shell with a transverse, coronal cut at the top to provide a hole for probe insertion. *Syn:* **phantom, vertical**.

NOTE—Measurement and uncertainty estimation procedures in this recommended practice are primarily based on SC2 members' experience with sagittally bisected horizontal phantoms; recommended procedures may require modification if used with upright phantoms.

3.66 phantom material: For purposes of this recommended practice, a material having the equivalent dielectric properties, i.e., permittivity and conductivity, as the tissue it represents.

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

3.68 polarization (radiated wave): That property of a radiated EM wave describing the time-varying direction and amplitude of the 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.

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

3.70 power: A physical quantity describing the rate of delivery or transmission of energy. In this recommended practice power will refer to radio frequency power expressed in units of watts (W).

3.71 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.

3.72 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.

3.73 probability distributions: **(A)** Normal: A probability distribution function that can be described by

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

where σ 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.

3.74 probe: For purposes of this recommended practice, a minimally perturbing device used for measuring a component 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 probe.**

3.75 probe antenna-length: The maximum physical dimension of the antenna element of a single-axis probe, or of the largest antenna element of a multiple antenna array.

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

3.77 probe-length: The length of the probe assembly including the high-resistance transmission line

3.78 probe-tip diameter: The maximum physical dimension of the dielectric encapsulation of the probe assembly measured at the location of the tip of the electric field probe.

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

3.80 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).

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

3.82 pulsed RF: A continuous-wave RF carrier signal that is amplitude-modulated at a known PRF with a controlled duty factor.

3.83 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.

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

3.85 readout electronics: Electronic apparatus for acquiring the probe output signal and converting it to a signal that can be read by the data acquisition and analysis apparatus.

3.86 reflected wave: A wave in a medium produced by reflections from objects or discontinuities in the medium or from a boundary of a different medium.

3.87 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. In this standard, 90% of the final value is assumed.

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

3.89 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 ,

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

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

3.90 sagittal (plane): For purposes of this recommended practice, the median plane of the head, i.e., a plane that divides the left from the right half of the head.

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

3.92 sensitivity: For a measuring device, the ratio of the magnitude of the device response, e.g., voltage, to the magnitude of the quantity measured, e.g., electric field strength squared.

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

3.94 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 (ρ).

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

SAR is expressed in units of watts per kilogram (W/kg) or equivalently milliwatts per gram (mW/g). Some literature, e.g., Pokovic [B120], refers to a so-called volume-SAR, expressed in units of mW/cm³, where mass density has been set to unity.

NOTES

1—SAR can be related to the E-field at a point by

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

where

σ = conductivity of the tissue (S/m)
 ρ = mass density of the tissue (kg/m³)
 E = rms electric field strength (V/m)

2—SAR can be related to the increase in temperature at a point by

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

where

ΔT = change in temperature (°C)
 Δt = 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.).

3.95 specific absorption rate—peak spatial-average: The maximum local SAR averaged over a specified 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.

3.96 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.

3.97 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.

3.98 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.

3.99 standing wave ratio: The ratio of maximum field strength (voltage) to minimum field strength along the direction of propagation of two waves traveling in opposite directions on a transmission line.

3.100 system check: For purposes of this recommended practice, the confirmation of the operational aspects of the SAR system for testing an individual device, to ensure system performance is within the acceptable range specified by the manufacturer. *Syn:* **system verification.**

3.101 system validation: For purposes of this practice, the verification of the performance specifications of the entire SAR measurement system by testing the system against known values or against other systems.

3.102 transverse plane: For purposes of this recommended practice, any one of the planes cutting across the body perpendicular to the sagittal and the frontal planes, dividing the body into superior and inferior parts.

3.103 uncertainty (assessment): For purposes of this recommended practice, 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 address only this category of uncertainty and cannot be used to obtain the total system uncertainty.

3.104 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 which were obtained by taking the positive square root of the estimated variances.

3.105 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%.

3.106 uncertainty (general): The estimated amount by which the observed (measured) or calculated value of a quantity may depart from the true value. 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.

3.107 uncertainty (phantom): Uncertainty that describes 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, and dimensions of a phantom.

3.108 uncertainty (source): Uncertainties in SAR distributions 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.

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

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

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

3.112 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 FDTD method, for solving EM problems.

3.113 waveguide: An enclosed system capable of guiding EM waves from one place to another. Usually it consists of a hollow metallic tube or a solid dielectric material.

4. Electric field (E-field) probe and readout electronics

4.1 Introduction

This subclause describes the instrumentation for the assessment of local SAR in shell phantoms filled with tissue-equivalent liquid using E-field measurements.⁷ 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. Recommended 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 sensor dipoles are currently employed in dosimetric systems designed for measuring the local SAR of low-power devices to satisfy compliance requirements. Since the scope of this standard 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 should be valid for measurements using other types of E-field sensors. The characteristics of typical E-field probes are described, for example, in Bassen and Smith [B8], Kanda [B84], Schmid et al. [B129], Spectrum Sciences Institute [B134], Strickland and Audeh [B135], and Stuchly et al. [B137]. Other types of E-field sensors have been and are being investigated, 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 must be much smaller than the wavelength in a tissue-simulating liquid, be isotropic, exhibit a linear response to the square of the incident electric field strength, and should 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. The E-field vector

⁷The rationale and the frequency dependence of the dielectric parameters of “head tissue” simulating liquid are described in Clause 5.

magnitude is the root sum square (RSS) of the three orthogonal components measured by the sensors, as shown in Equation (5):

$$|E| = \sqrt{|E_1|^2 + |E_2|^2 + |E_3|^2} \quad (5)$$

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 extract 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 rms of the corresponding E-field component. The probe itself consists of three such sensors and has three output ports, each one providing a low-frequency dc voltage resulting from the filtering performed by the resistive feed-line, which acts as a distributed R-C low-pass filter of the rectified sensor outputs. The magnitude of the E-field is shown in Equation (6)

$$|E| = \sqrt{\frac{V_1}{\gamma_1} + \frac{V_2}{\gamma_2} + \frac{V_3}{\gamma_3}} \quad (6)$$

where V_i is the open circuit voltage and γ_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.

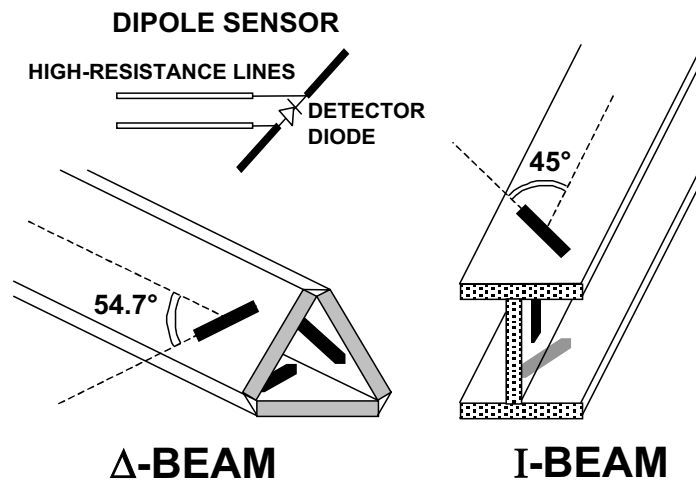


Figure 1—Typical E-field probe construction. A “Δ-beam” (or “triangular-beam”) or an “I-beam” dielectric structure supports the three miniature and mutually orthogonal sensor dipoles (Faraone et al. [B44])

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:

- 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, etc., from the ambient and nearby equipment
- f) Other physical influences, e.g., temperature, etc., that could change probe performance

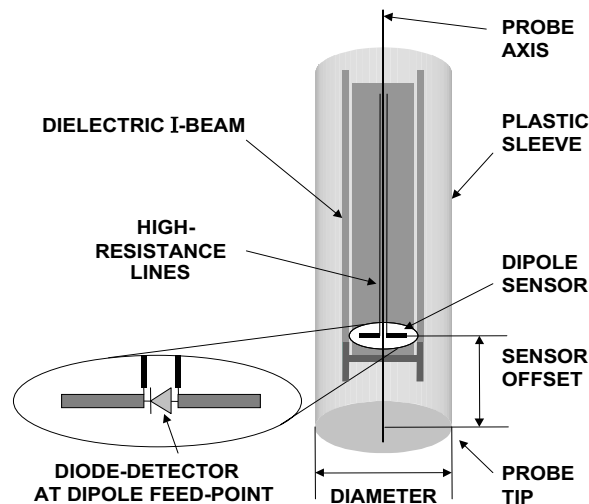


Figure 2—E-field probe features. Sensor offset is measured from the geometric center of the sensors to the tip of the probe enclosure. Sensor displacement is measured from the dipole feed-points to the probe axis (Faraone [B44]).

The sensitivity of the probe output to these factors should 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 should be preceded by a complete characterization of the probe independently of the measurement system, in order to evaluate the probe response to the above factors. It will also be necessary to calibrate the probe in different tissue-equivalent liquids. Each calibration should indicate the range of parameters (permittivity, conductivity, frequency, temperature) for which the assessed probe uncertainty is valid. Some of the above influences can be partially compensated in the output measurement system with techniques such as filtering, frequency compensation, and diode response linearization (Pokovic [B120]). 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 1309-1996). However, these techniques are not described in this standard because use is typically not required for SAR compliance testing.

Because of the high-resistance lines and the use of unbiased detector diodes, the typical source impedances of miniaturized E-field probes may range from several hundred $k\Omega$ to several $M\Omega$. 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.

Two different approaches are recommended for probe calibration and characterization:

- 1) Calibration and characterization of the probe together with the readout electronics and the post-processing system. This is preferable if the probe is solely used in a specific system. If the probe is calibrated with different readout electronic devices, manufacturing variations that result in differences in input characteristics from unit to unit must be considered in the uncertainty

evaluation. Even when an E-field probe is calibrated with its associated instrumentation and readout electronics, it is suggested that the probe output performance be evaluated with and without the processing and compensation system, so that the probe characteristics are known explicitly [see step 2)].

- 2) Calibration and characterization of the probe without the readout and post processing system, i.e., at the probe connector. The acceptable input characteristics of the readout electronics must be specified, as well as the range of electric field strengths used during calibration and characterization. The probe can then be used in any system that matches these characteristics. Deviations in the input characteristics as well as all errors introduced by the instrumentation must be considered in the uncertainty analysis (see 4.4).

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. Two components of isotropy can be defined as:

- a) *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,
- b) *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.

Deviation from the ideal isotropic response can result 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 must be assessed within a specific dielectric medium of intended use. Depending on the setup being used, this is accomplished by performing E-field measurements while carrying out some or all of the following steps:

- i) Rotate the probe around its longitudinal "axis"
- ii) Rotate the field propagation direction from parallel to the probe axis (frontal incident) to normal to the probe axis (lateral incident)
- iii) Rotate the field polarization from normal to parallel to the incidence plane formed by the probe axis and the incident field direction (this definition breaks down when the incidence direction is along the probe axis; in that case, probe rotation replaces field polarization rotation)

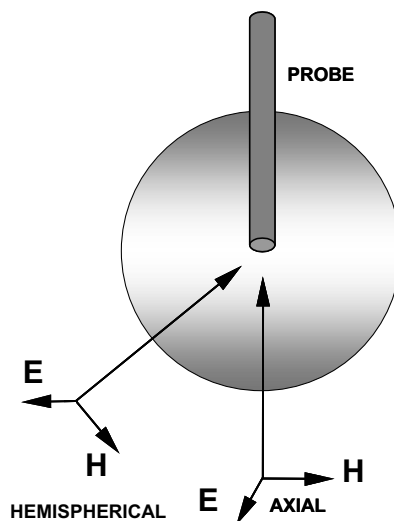


Figure 3—Schematic representation of axial and hemispheric probe isotropy

The following setups and procedures are recommended for isotropy assessment: A spherical flask filled with tissue-equivalent liquid with the tip of an E-field probe (geometric center of the sensors) located at its center and a half-wave dipole tangential to the surface of the flask at a specified distance. A flat phantom with a half-wave dipole parallel to the bottom of the phantom at a fixed distance, with the probe positioned inside the phantom and above the dipole feed-point

The recommended isotropy assessment procedures are described in detail in A.5. The isotropy should be characterized at least for one frequency in the band of interest, e.g., the 800–900 MHz and 1800–1900 MHz bands. The isotropy uncertainty is the maximum deviation of the measured SAR with respect to the average SAR over all measurements with an assumed rectangular error distribution.

Due to the high conductivity of liquid-filled head-shaped phantoms, the E-field polarization at the field maximum is predominantly parallel to the phantom surface. If the probe positioning system has a limited probe inclination with respect to the phantom surface, the rotation angle (item d) this clause) in the isotropy assessment can be limited to the maximum possible range for the system. If the isotropy uncertainty is assessed within a limited range, it must be indicated in the field-probe calibration and compliance documentation along with a description of the probe positioning system.

4.2.2 Spatial resolution

Spatial resolution of a probe is 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. 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 may cause the SAR peaks to be closer than a probe diameter.

Due to the physical dimensions 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 integrates the field over a finite volume according to the geometric configurations of the sensors within the probe. This averaging process may 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. For peak spatial-average SAR measurements, the spatial resolution error is generally small as long as the probe-tip diameter is less than 8 mm.

The effect of the probe spatial resolution on the 1 g and 10 g peak spatial-average SAR is negligible for probes with diameters smaller than 8 mm (Faraone [B44]). Therefore, dosimetric E-field probes with an external plastic sleeve diameter at the probe tip (center of the sensors) no larger than 8 mm should be used for all tests described in this recommended practice.

The following two test setups can 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. The probe is moved through the SAR peaks between the opposite potential pairs along a horizontal line flush with the open termination of the quadrupole.
- 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 between the dipole feed-points (see Figure A.7) at a fixed height from the phantom surface. Two distinct SAR peaks with a null in between should be encountered.

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

4.2.3 Boundary effects

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

- a) Distance between the probe tip and the phantom surface or media interface
- b) Extrapolation algorithm used for determining the SAR at the surface of the phantom
- c) Frequency, field gradients, and field decay in the medium, at the measurement location
- d) Averaging volume (1 g or 10 g)
- e) Optional implementation of compensation routines for reducing the boundary effects

A setup for assessing the boundary effect is described in A.8. It consists of a rectangular waveguide partially filled with head tissue-equivalent liquid that is separated from the air-filled portion of the waveguide with an impedance-matching dielectric slab (Pokovic [B120]). Alternatively, a flat-phantom/dipole configuration can be employed.

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 half the probe diameter. 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 surface. Errors can be reduced further if the probe tip is kept at distances of one probe diameter or more. Boundary effects can be evaluated by comparison with the response of a probe having a smaller tip diameter (Pokovic et al. [B122]). In practice, there is a tradeoff between increased distance to reduce the boundary effects and the resulting possible increase in extrapolation error (see E.5).

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. Deviations from the ideal response of diode detectors are determined during probe calibration and are compensated during measurements. Errors that can be assessed during probe and system calibration that can be compensated in all measurement situations include the following:

- a) Differences among sensor sensitivities
- b) Deviation from linearity of the sensor response with increasing incident electric field strength

If such compensation is used, the probe measurement uncertainty assessment should be performed with the processing and compensation routines included.

4.3.1 Probe linearity

Detector diodes at the dipole feed-point are used to rectify the sensor voltage output. The rectified signal is transmitted through resistive (RF-transparent) lines to the voltage measuring system. At low field strength levels the output voltage is proportional to the square of the amplitude of the incident field; at higher signal levels, the output voltage is not linearly proportional to E^2 , but becomes proportional to E . A typical crossover point for the rectified output voltage of low-barrier silicon Schottky diodes is about 100 mV, but even at 3 mV the deviation from square-law response is already greater than 0.1 dB. Such compression may lead to an underestimation of the actual SAR at high field strength conditions.

The diode compression should 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 output signal is distributed among the three sensors. For example, the same field would produce a different reading if detected by one sensor alone compared with detection among all the sensors.

For pulse-modulated signals, the compensation for diode compression should be carried out on the temporal signal and the output should follow the amplitude modulation. 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 envelope modulation of the signal at the amplifier input may be attenuated. If the system measures a time-averaged detector signal that is below the diode compression level, the peaks of a modulated signal could still be above this level. Various algorithms can be employed to compensate for the diode compression.⁸ Even though good linearization is typically achieved using polynomials, in some cases the use of piece-wise curvilinear functions may be necessary (Chen [B22]; Hoer et al. [B67]; Jokela et al. [B81]; Potter and Bullock [B123]; SPEAG [B132]).

The "peak detector effect" inherent in diode detectors is another nonlinear effect that exists only with amplitude modulated signals. The nonlinear diode impedance converts the probe from an average to a peak detector for high power pulsed signals by rectifying the signal and charging the capacitance of the amplifier. An increase in the resistive-line impedance can minimize the peak detector effect by reducing the dependence of the detected signal timing characteristics on the variable source impedance of the diode (Pokovic [B120]).

⁸Compensation for diode compression may be performed in various ways. If system video bandwidth is large enough such that the voltage at the amplifier input follows the envelope modulation of the RF signal, then the linearization algorithm can be applied sample by sample. If the video bandwidth is too narrow such that the envelope modulation cannot be reproduced at the amplifier input, then a priori information regarding the modulation, e.g., its duty factor, should be incorporated in the linearization algorithm. One noticeable exception to this occurs for CDMA signals, whose envelope modulation bandwidth is much wider than the typical system video bandwidths. In this case, the same linearization parameters used for CW signals may be employed (Di Nallo and Faraone [B37]).

Linearity errors are determined from the sensor output voltage versus applied average power response curve. The assessment should be carried out with all compensation procedures used in the measurement system activated. This can be done in any setup in air or in liquid since the dynamic response is a function of the diode output voltage only. Each sensor channel must be characterized over the output voltage range from well below diode compression to a maximum sensor voltage that corresponds to a peak SAR of 100 W/kg. The following modulations should be tested and documented in the probe calibration certificate:

- a) CW signals up to an equivalent SAR of 100 W/kg⁹
- b) Pulsed signals with a duty factor of 1:10 and repetition rate of 11 Hz up to an equivalent peak SAR of 100 W/kg (low repetition rate)
- c) Pulsed signals with a duty factor of 1:25 and repetition rate of 1 kHz up to an equivalent peak SAR of 100 W/kg (large repetition rate)

The CW measurements that are below the diode compression threshold should be linearly extrapolated to cover the full power range used in the measurements. This gives the ideal linear response for the sensor. The maximum probe nonlinearity error is the maximum difference of the measured data from this ideal linear response. Any differences in probe sensitivity to the CW and pulse modulated signals are included in this error.

4.3.2 Offset error

Errors that are generated by the probe diode detector and post detection system and by the specific environmental situation also occur. These errors translate typically to an offset voltage at the probe output, which can be split into different types of contributions.

Offset errors associated with the probe only include the following:

- a) Thermal noise associated with the diode incremental resistance, high resistance lines of the probe, high input impedance of the electronics (1–3 μV p-p from 0.1–10 Hz)
- b) Photovoltaic effects in the detector diodes in transparent probe tips (several μV)
- c) Chemically generated voltages in impurities in the resistive lines and connections (0–100 μV)
- d) Static charges built up by moving the probe in the tissue-equivalent liquid (up to 1 μV)
- e) ELF signal pickup in the lines that is rectified by the sensor diodes

Offset errors associated with the electronics independent of the probe include:

- Offset voltage of the input amplifiers; if offset compensation is not provided, the offset drift with time and temperature may become unacceptable
- Direct pickup and rectification of RF signals from device under test, at the amplifier inputs

Offset errors of the readout electronics with the probe include

- 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 lines that are generated by
 - i) Low-frequency conducted pickup from power lines or the positioner motors
 - ii) Different ground potentials between the positioner and the source (ground loops)
 - iii) Conducted interference induced on the a/c power lines from the data evaluation system (test control computer)

⁹The IEEE Std C95.1-1999 limit for the extremities for exposures in controlled environments (occupational exposure) is 20 W/kg.

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 should 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) so that it can be partially compensated for in the system. While the rectified signal is always unipolar, the offset can be bipolar.

The system offset is assessed with the verification (*system check*) setup of 8.2. Since the offset effect is frequency independent it can be determined at a single frequency, e.g., at the mid-band channel of a test device. The input power of the dipole is varied such that the local SAR value at the probe corresponds to approximately 1, 0.5, 0.2, 0.1, 0.05, 0.02, 0.01 W/kg. Offset effects are more important at low signal levels. If the deviation from linearity at 0.01 W/kg is less than 20%, the errors due to the compensated readout electronics can be assumed to be negligible. Otherwise, the offset error and statistics (mean value and standard deviation) are evaluated by performing several SAR measurements with an RF source.

4.4 Probe calibration

The response of the probe's sensors depends on the dielectric parameters of the surrounding media and the signal frequency. The probe must 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 must be assessed, e.g., by calibrating the probe in different tissue-equivalent liquids exhibiting slight differences ($\pm 10\%$) in the dielectric parameters. Applicable frequency ranges for calibrations are discussed in 4.4.1.1. The measurement 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 must be 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 must be carefully determined. This can be done by

- a) Measurements with calibrated field probes (transfer method)
- b) SAR assessment by temperature measurement
- c) Input RF power measurements leading to analytical field values at the calibration point under specific experimental conditions, e.g., rectangular waveguide

Since the input characteristics of the data acquisition electronics influence the signal at the probe output, they must be reported in the probe calibration report. The probe calibration is only valid when used with data acquisition systems having the same input characteristics. The data acquisition system must 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 errors must be specified (see A.9).

The calibration fields in lossy media are gradient fields. Since the field may vary over the probe-tip region, the exact location of the calibration center (nominal field point) of the probe must be indicated. The nominal field point should 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 measuring the 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 analytical calibration techniques, are presented in A.3.

4.4.1 Recommended procedures for probe calibration

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 is made deep enough to guarantee 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 is used to calibrate the probe. The probe is rotated around its axis and the measured probe response is averaged to account for any axial isotropy errors in the calibration.

For frequencies below 800 MHz, temperature transfer calibration is recommended because the waveguide size becomes relatively large. The setup for this calibration consists of a flat phantom with a dipole source. The field is measured with the probe under calibration in the liquid directly above the dipole feed-point. 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. As above, a probe rotation around its axis is performed and the measured probe responses are averaged to account for the axial isotropy error in the calibration.

Table 1 summarizes the recommended probe calibration procedures.

Table 1—Recommended probe calibration procedures

Frequency < 800 MHz	Thermal calibration ^a
Frequency ≥ 800 MHz	Waveguide calibration ^b

^aIf large calibration waveguides are available, analytical calibration is preferable.

^bWhen a calibration waveguide is not available for a specific frequency, thermal calibration is employed.

4.4.1.1 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 recommended that information be provided on the calibration certificate to substantiate the calibration validity range and associated uncertainties.

4.4.1.2 Calibration environment

The ambient conditions defined in Table 3 should be maintained during probe calibration.

4.4.2 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, should be within the calibration accuracy range recommended by the manufacturer or other site compliance requirements. Documentation should be available showing that instrumentation calibrations are traceable to national or international metrology institutions, e.g., NIST in the US, NPL in the UK, etc.

5. Phantom models

In order to evaluate the near-field exposure produced by wireless handsets, phantom models simulating human anatomies have been used. These models vary from simplified (Spectrum Sciences Institute [B133]; Wojcik and Cardinal [B150]) to more human-like (“anthropomorphic”) models (Balzano et al. [B6]; Hombach et al. [B68]; Kuster and Balzano [B91]; Wang and Fujiwara [B145]; Yu et al. [B151]). In addition to the different sizes and shapes of the phantom models, various manufacturers and test laboratories have used different dielectric properties for the tissue equivalent liquids and different handset test positions. In the absence of standardized tissue property parameters and device test positions, the test results from different laboratories for the same wireless handset may vary due to different test configurations. When test results approach the applicable SAR limits, additional error margins are often needed to ensure that the test results are reliable. To reduce measurement variations, it is necessary to define a phantom model with a standardized size and shape, as well as specific parameters for the tissue-equivalent liquids, so that all laboratories can assess SAR using the same standardized model. The use of the Specific Anthropomorphic Mannequin (SAM) phantom and handset test positions in standardized measurement procedures will reduce lab-to-lab variability. As described in this clause (and also in 1.4), the combination of higher tissue conductivities, a large head size, a thin ear spacer, and the exclusion of a hand holding the handset were chosen to provide a conservative estimate of the peak spatial-average SAR associated for the operating configurations expected by typical wireless handset users.

5.1 Phantom head models: requirements

5.1.1 General

In order to assess the SAR associated with the near-field exposure conditions encountered under normal use conditions of a wireless handset, i.e., with handset held against the ear, the phantom model should resemble a typical user. For wireless handsets intended for operation while held next to the body, a model of the torso or 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. [B72] 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 normal use 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.

For the typical setup of a sagittally-bisected phantom, each half is placed on its side, and the device under test is placed underneath. To minimize reflections from the upper surface of the liquid, the depth of the liquid should be at least 15 cm, which is approximately the distance between the ears of a whole-head phantom. The test methods described in this standard are focused on sagittally bisected phantoms. Other phantom configurations may be used, such as an upright phantom with a coronal cut at the top of head, for which modified test procedures and additional uncertainty analyses not described in this recommended practice may be required.

5.1.2 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 densities have a strong influence on the local SAR. These distances depend on the head shape and the pinna representation. Results from Schönborn et al. [B130] 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 curvature radius is more like a flat structure with the tissue boundary closer to the antenna, thereby capturing more energy than a smaller head. Numerically computed SAR results in Gandhi et al. [B58] showed a higher peak 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 child's head model (Schönborn et al. [B130]). 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 [B97], Lee et al. [B98], and Watanabe et al. [B146] also show that large head models provide conservative SAR estimates.

Since a larger head has a higher SAR due to the larger curvature radius (which puts the head slightly closer to the antenna), for a constant pinna thickness (Schönborn et al. [B130]) a large male head with a compressed simulated pinna represents a conservative case for men, women, and children. The phantom model described in 5.3 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 normal use configurations. Additional discussion about the rationale of selecting the shape and dimensions of the SAM phantom is given in 1.4.

To reduce interlaboratory variations 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 to ensure that manufacturing tolerances have a minimal effect on measured SAR. Phantom tolerances should be confirmed by the manufacturer and declared with a production certificate.

5.1.3 Homogeneous versus heterogeneous head models

The dependence of the peak spatial-average SAR on the physical model of the head was analyzed in Kuster et al. [B94] and shown to have small dependencies on the internal heterogeneous anatomy. 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. [B6] and Cleveland and Athey [B30]. 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. [B58], Hombach et al. [B68], and Meier et al. [B103], measurements in homogenous head models at 900 MHz and 1800 MHz can overestimate or underestimate SAR depending on the selected tissue parameters. A conservative approach for assessing SAR can be achieved by choosing suitable tissue dielectric parameters, which provide some overestimation based on 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, most 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.

5.1.4 The external ear (pinna)

5.1.4.1 Modeling the 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, appropriate test positions must be established between the handset and the phantom to ensure 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 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 [B17]; Gandhi and Lazzi [B57]; Gandhi et al. [B58]; Watanabe et al. [B148]). Because of the very high SAR induced in the pinna, and to maximize SAR in the head, SCC34/SC2 performed an extensive analysis of the topic. The following basic issues were addressed:

- a) How the phantom ear could be constructed to enable measurements to be made in this region 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 model of the pinna 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" model of the pinna should be used instead of a "lossy" pinna. 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 with the actual shape of the human pinna on the inner surface of the phantom. This indentation is then filled with simulated head material (a lossy dielectric liquid) when the head is filled.

The following published results were considered:

- 1) Watanabe et al. [B148] 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.
- 2) Yu et al. [B151] 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.
- 3) Based on numerical modeling results, Gandhi and Lazzi [B57] 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.
- 4) Balzano et al. [B6] used a thin low-loss dielectric spacer in a physical head model to represent the pinna. Wojcik and Cardinal [B149] 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. [B59].

- 5) Kanda et al. [B86] 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 $6\text{ cm} \times 3.2\text{ cm} \times 0.2\text{ cm}$ 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.
- 6) Christ et al. [B26], [B27] 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 SAR inside the MRI-based head model with lossy pinna versus the peak 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. [B26] 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 [B17]) pertain to a lossy anatomically accurate pinna derived from MRI scans, and are not applicable to the pinna model selected in this recommended practice.

SCC34/SC2 also studied the feasibility of measuring SAR inside a model of a lossy pinna. When the pinna of the 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, SCC34/SC2 concluded that for purposes of this recommended practice, a thin low-loss dielectric spacer shaped like a human ear should 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. The resulting homogenous head model with a thin, lossless ear spacer is expected to ensure that the expected SAR in the head of a significant majority of users is not underestimated.

5.1.4.2 Peak spatial-average SAR limits for the pinna¹⁰

Some contemporary handsets are capable of producing a spatial peak (local) SAR in the pinna that exceeds 1.6 W/kg when averaged over 1 g of tissue, which exceeds the basic restrictions (BR) of some contemporary RF safety standards. Numerical studies, however, have shown that typical modern handsets produce less than 4 W/kg when averaged over 10 g of pinna tissue (Lazzi et al. [B96]; Schiavoni et al. [B127]), which is the peak spatial-average SAR value for the extremities found in contemporary standards such as IEEE Std C95.1-1999. Since SCC34/SC2 does not have the expertise or responsibility to establish health and safety limits, the chairman of SC2 submitted a request to the IEEE International Committee on Electromagnetic Safety ICES (SCC28), the committee that is responsible for developing the IEEE C95 series of RF safety standards) that they examine this issue and consider whether the IEEE Std C95.1-1999 peak spatial-average SAR values for the extremities should apply to the pinna. After deliberation, ICES/SC4 (Safety Levels with Respect to Human Exposure, 3 kHz–300 GHz) recommended to ICES (SCC28) that it would be appropriate to apply the peak spatial-average SAR values currently used for the extremities to the pinna, i.e., the pinna should be considered an extremity. For extremities, IEEE Std C95.1-1999 allows a peak spatial-average SAR of 4 W/kg averaged over 10 g of tissue for the uncontrolled exposure environment and 20 W/kg for the

¹⁰This subclause is for reference only. It is not within the scope of SCC34 to establish basic restrictions such as for peak spatial-average SAR values.

controlled environment. ICES conducted a formal ballot and the recommendation was approved. At the same time, ICES/SC1 (Measurements, Instrumentation, and Computation) developed a method for numerically averaging the measured or computed SAR over 1 g or 10 g of tissue in the head and extremities (IEEE Std C95.3-2002), which includes the hands, wrists, feet, ankles, and pinnae.

5.1.5 Hand and device holder considerations

Because the hand when holding a handset is in the near field of the antenna, some amount of energy absorption in the hand is expected. However, higher peak spatial-average SAR is permitted in extremity tissues, i.e., 4 W/kg averaged over 10 g of tissue in the hands, wrist, feet, and ankles (IEEE Std C95.1-1999) or 4 W/kg averaged over 10 g of tissue in the limbs (ICNIRP [B69]). Numerical and experimental studies have shown that SAR in the hand is low compared with the SAR in the head (Francavilla et al. [B49]; Gandhi et al. [B58]; Jensen and Rahmat-Samii [B78], [B79]; Kuster et al. [B94]; Watanabe et al. [B147]). Moreover, the large number of possible finger positions and different practices of holding the handset makes it difficult to specify a standard “hand phantom.” Similarly to the pinna considerations, presently available E-field probes and experimental methods cannot be used to accurately measure SAR inside a realistic model of the hand. Preliminary numerical modeling results in Meyer et al. [B104] show that for a specific generic handset shape and specific parameterized finger positions, peak spatial-average SAR in the head may increase. Additional investigation of these unique results is needed by SCC34/SC2 before incorporating the test complexities associated with the use of hand phantom. For these reasons, hand models are not considered in this recommended practice. If necessary, a hand model may be developed in the future. Handsets are typically tested without a hand, which usually results in an overestimation of the SAR in the head (Balzano et al. [B6]; Kuster et al. [B94]). 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, ϵ_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) should be done by replacing the holder with low-density, low-permittivity dielectric blocks, e.g., foamed polystyrene, or affixing the handset to the phantom using nonconductive tape.

5.2 Tissue and tissue-equivalent liquid properties

5.2.1 Dielectric properties

The dielectric properties of tissues have been extensively studied over the past several decades (Burdette et al. [B16]; Gabriel et al. [B53]; Schwan and Piersol [B131]; Stuchly and Stuchly [B136]). 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. [B56]). In this recommended practice, all tissue dielectric properties are derived according to the most recent and comprehensive data reported in Gabriel [B51] and Gabriel et al. [B54], [B55]. Phantom materials with the same dielectric properties as tissues have been developed for RF dosimetry studies and medical applications, e.g., Chou et al. [B24]. The adoption and use of standardized tissue-equivalent phantom materials (liquids) minimizes one of the major components of SAR measurement uncertainty.

The choice of tissue dielectric parameters for homogeneous tissue-equivalent liquid determines the extent of any over- or underestimation when compared with SAR results from heterogeneous head modeling. Detailed internal head anatomies must be considered when selecting the equivalent tissue parameters, and these parameters must be chosen carefully to ensure that the SAR measured in the homogeneous phantom does not underestimate what is expected in an actual human head. The dielectric parameters of most simulated tissues generally represent an average value of several different tissue layers. Phantom tissue materials may be liquid (Hartsgrove et al. [B64]), gel (Andreucetti et al. [B1]; Bini et al. [B10]; Chou et al. [B24]; Guy [B62]; Guy and Chou [B63]; Lagendijk and Nilsson [B95]) or solid (Guy [B62]; Tamura et al. [B139]).

Liquids used as phantom materials, which are usually optically transparent, should have a low viscosity to prevent an impediment to movement of the E-field probe. A number of brain-equivalent liquid recipes have been developed to test wireless communications devices. Yu et al. [B151] reports a nontransparent brain-equivalent liquid, which requires periodic stirring to maintain homogeneous tissue dielectric properties in the material. For the purposes of this recommended practice, new head-equivalent tissue parameters were derived based on numerical models of planar layers to represent the various head tissues (Drossos et al. [B38]). The new head-equivalent target dielectric parameters are given in 5.3.1, with suggested mixture recipes given in Annex C.

5.2.2 Characterization of tissue-equivalent liquid dielectric properties

For a given relative permittivity, SAR is directly proportional to the tissue conductivity. Therefore, it is important that the dielectric parameters of the tissue-simulating materials are accurately characterized before use in a phantom for SAR measurements. Because the dielectric properties vary with temperature, phantom tissues are usually developed to have dielectric properties at room temperature (18 °C–25 °C) that are the same as those tissues at body temperature (37 °C). In the microwave frequency range, the increase in conductivity for high water-content tissue is 2% per degree Celsius, while the permittivity decreases 0.5% per degree Celsius (Johnson and Guy [B80]). However, brain tissue shows a different temperature dependence (Foster et al. [B48]; Schmid et al. [B128]). While the relative permittivity of brain tissue also decreases at higher temperatures, the conductivity increases at low frequencies and decreases with temperature at higher frequencies, with this transition occurring at about 1 GHz.

Liquid or gel tissue-equivalent materials can be characterized using slotted line (Chou et al. [B24]), coaxial probe (Burdette et al. [B16]; Gabriel et al. [B52]; Stuchly and Stuchly [B136]), or TEM line techniques (Toropainen et al. [B142]). For a SAR assessment to be suitable for the protocol of this standard, the measured permittivity and conductivity of tissue material should be within the acceptable limits described in 5.3.1. Liquid-filled phantoms should be characterized periodically (at least within 24 hours of any full-compliance handset SAR test) to ensure that the dielectric parameters are within $\pm 5\%$ of the target values and excessive evaporation has not occurred. The temperature variation in the liquid during SAR measurements must be within ± 2 °C of that recorded when the liquid dielectric properties were characterized.

Standard procedures for tissue-equivalent material characterization, handling, and maintaining dielectric parameters for extended durations should be established at each laboratory to minimize the variations associated with the tissue parameters and improve measurement repeatability. Annex B describes the recommended techniques for measuring the dielectric properties of tissue-equivalent liquids.

5.3 Recommended phantom models

5.3.1 Head tissue-equivalent liquid

A simple analytical model of an infinite half-space layered tissue model exposed to a plane wave was utilized to investigate the impact of impedance matching, scattering, standing waves, etc., on the peak spatial-average SAR (Drossos et al. [B38]). The tissue layers were varied in composition and thickness to represent the anatomical variations of the exposed head region within the user group including adults and children (within the 10th and 90th percentile population levels). For each frequency, the tissue combinations and thicknesses that produced the highest peak spatial-average SAR values averaged over 1g and 10 g were evaluated. The corresponding homogeneous dielectric properties were derived by selecting the equivalent relative permittivity to be the average of all considered tissues, and the conductivity was selected to produce the same (or slightly higher) peak spatial-average SAR values. The Cole-Cole tissue dielectric property data were used in this analysis (Gabriel [B51]). The applicability of this layer method to near-field exposure conditions was confirmed by replacing the incident plane-wave fields (source) with half-wave dipole and quarter-wave monopole sources in proximity to the layered structures, as well as by comparison with results

from MRI-based heterogeneous human head models of adults and children (Burkhardt and Kuster [B17]; Hombach et al. [B68]; Meier et al. [B103]; Schönborn et al. [B130]).

Table 2 shows the permittivities and the larger of the two conductivities resulting from averaging over 1 g or 10 g of the head tissue-equivalent material (Drossos et al. [B38]). Linear interpolation should be used to obtain dielectric properties at other frequencies within the range. Suggested formulas for the head tissue-equivalent liquids are listed in Annex C. The target parameters are derived to represent head tissue where nominal temperature is 37 °C. Liquids for SAR testing should be mixed to produce the target values at actual ambient liquid and laboratory temperatures. Until verified recipes are available for head tissue-equivalent liquids that give both measured permittivity and conductivity within $\pm 5\%$ of the Table 2 target values in the 2–3 GHz range, the following tolerances are recommended:

- a) For frequencies in 300 MHz to just under 2 GHz, the measured conductivity and relative permittivity should be within $\pm 5\%$ of the target values (see E.3.3 for tissue parameter measurement uncertainty evaluation procedures)
- b) For frequencies in the range of 2–3 GHz the measured conductivity should be within $\pm 5\%$ of the target values. The measured relative permittivity tolerance can be relaxed to no more than $\pm 10\%$, but efforts should be made to obtain target values as closely as possible using available recipes. Effects on the SAR of the relative permittivity deviation from the target values should be included in the uncertainty evaluation.

Table 2—Target dielectric properties of head tissue-equivalent material in the 300–3000 MHz frequency range

Frequency (MHz)	Relative permittivity (ϵ_r)	Conductivity (σ) (S/m)
300	45.3	0.87
450	43.5	0.87
835	41.5	0.90
900	41.5	0.97
1450	40.5	1.20
1800–2000	40.0	1.40
2450	39.2	1.80
3000	38.5	2.40

5.3.2 Phantom shape and size

5.3.2.1 Anthropomorphic head phantom

The phantom shell is made of low-loss dielectric material, with shape and selected dimension parameters from the 90th-percentile anthropometric data corresponding to the adult male head as tabulated by the US Army (Gordon et al. [B59]). As discussed in 5.1.4, an ear spacer was selected rather than an anatomical ear. Consequently the distance between the head and the upper posterior portion of the compressed ear (helix) does not correspond to the 28.8 mm air gap of the Army data. The shape of the head is derived from the lines and curves shown in Figure D.3. The first step in defining a standard phantom was fabrication of a 3-D hairless head and neck clay sculpture using dimensions and shapes taken from the selected US Army numbers. The sculpture dimensions were optically scanned and entered into the CAD file.

Figure 4 shows the front, back, and side views of the SAM phantom. The center-of-mouth reference point is labeled “M,” the left ear reference point (ERP) is marked “LE,” and the right ERP is marked “RE.” Each ERP is 15 mm along the B-M (back-mouth) line behind the entrance-to-ear-canal (EEC) point, as shown in Figure 5. The Reference Plane is defined as passing through the two ear reference points and point M. The line N-F (neck-front), also called the reference pivoting line, is normal to the Reference Plane and perpendicular to both a line passing through RE and LE and the B-M line (see Figure 6). Both N-F and B-M lines should be marked on the exterior of the phantom shell to facilitate handset positioning. Posterior to the N-F line the ear shape is a flat surface with 6 mm thickness at each ERP, and forward of the N-F line the ear is truncated, as illustrated in Figure 5. The ear truncation is introduced to preclude the ear lobe from interfering with handset tilt, which could lead to unstable positioning at the cheek. The SAM CAD file is contained on the compact disc (CD) included as a normative part of this recommended practice. Figure D.4(a), Figure D.4(b), Figure D.4(c), Figure D.4(d), Figure D.4(e), Figure D.4(f), and Figure D.4(g) show cross-sectional views of SAM in planes parallel to and in 10-mm increments for ± 30 mm from the Reference Plane.

Phantom shells for use with the test procedures in this recommended practice should be manufactured using the CAD file of the SAM model. Typically, when used in a horizontal configuration, the SAM phantom shell is bisected along the mid-sagittal plane into right and left halves. Testing is required on both right and left sides, since the location of the peak SAR is initially unknown. The perimeter sidewalls of each phantom half are extended to allow filling with liquid to a depth that is sufficient to minimize reflections from the upper surface (air-liquid interface). One possible implementation of a perimeter extension is shown in Figure 7. For the 300 MHz–3 GHz frequency range, reflections are minimized with a liquid depth of at least 15 cm, which is roughly the distance between the ears of the whole-head SAM model. The liquid depth should be measured from the ERP (inside the SAM phantom) to the air-liquid interface.

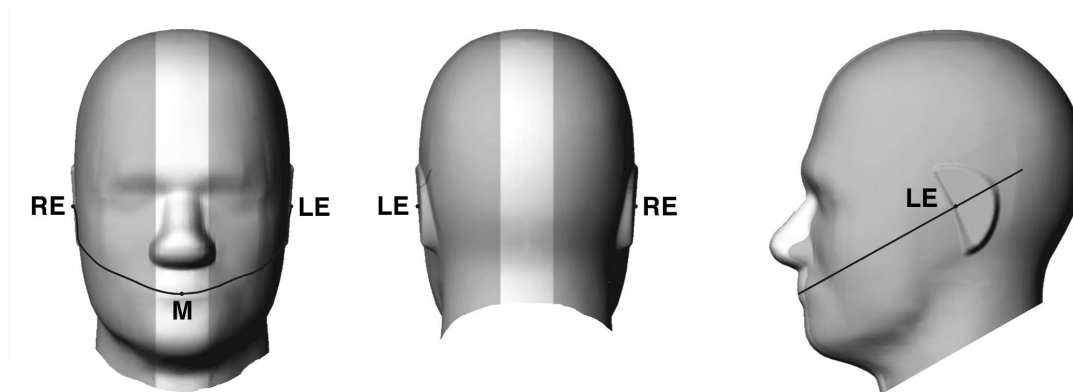


Figure 4—Front, back, and side views of SAM (model for the phantom shell). Full-head model is for illustration purposes only—procedures in this recommended practice are intended primarily for the phantom setup of Figure 7. Note: The center strip including the nose region has a different thickness tolerance.

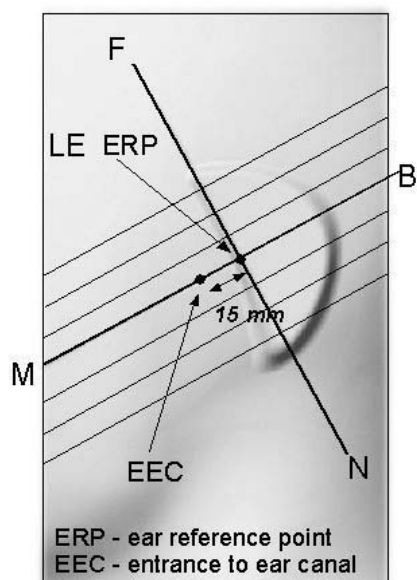


Figure 5—Close-up side view of phantom showing the ear region, N-F and B-M lines, and seven cross-sectional plane locations (see D.3)

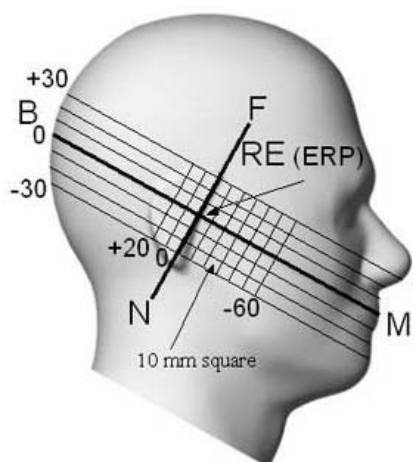


Figure 6—Side view of the phantom showing relevant markings and seven cross-sectional plane locations (see D.3)

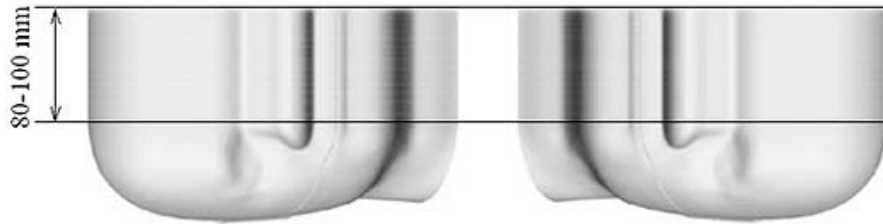


Figure 7—Sagittally bisected phantom with extended perimeter (shown placed on its side as used for SAR measurements)

5.3.2.2 Phantom shell

The phantom shell with integral ear spacer should be constructed from chemical-resistant, low-permittivity and low-loss material, with relative permittivity less than 5 and loss tangent less than 0.05. The shape of the phantom shell shall have a tolerance of less than ± 0.2 mm with respect to the SAM CAD file. In any area within the projection of the handset, the shell thickness shall be $2 \text{ mm} \pm 0.2 \text{ mm}$, except for the ear and the extended perimeter walls. The phantom shell shall be made of materials resistive to compounds used for making tissue-equivalent liquids listed in Annex C, in order to avoid damage and preserve the ± 0.2 mm tolerances. For noncritical areas, i.e., the central strip containing the nose, as shown in Figure 4, the thickness tolerance is allowed to be within ± 1 mm.

5.3.3 Flat phantom

A flat phantom should be used with the recommended tissue-equivalent liquid for *system check* and *system validation* purposes only (see Clause 8). The minimum transverse dimensions (width and length) should be such that the SAR results are not affected by more than 1% compared to a phantom with larger dimensions. For a half-wavelength dipole source, the length should be at least 0.6 times the wavelength in air in the major dimension, and width should be at least 0.4 times the wavelength in air in the minor dimension, with the bottom surface area larger than a corresponding ellipse (see Chavannes and Christ [B20]; D.1). For 800 MHz–3 GHz, the dimensions of the flat phantom should be $22.5 \text{ cm} \times 15 \text{ cm}$ in the major and minor axes, respectively (corresponding to minimum transverse dimensions at 800 MHz). The relative permittivity of the phantom shell material should be less than 5 and the loss tangent less than 0.05. The thickness of the flat phantom bottom section shall be 2 mm for the frequency range of 800 MHz–3 GHz and less than 6.5 mm for frequencies below 800 MHz. The thickness shall be uniform within a tolerance of ± 0.2 mm. The phantom shell materials should be resistive to compounds used for making the tissue-equivalent liquids listed in Annex C in order to avoid damage and preserve the ± 0.2 mm tolerances. When filled with liquid to the 15 cm minimum depth, the sag of the bottom section inner surface in the region directly above the source (e.g., dipole) should be less than 1% of a wavelength in air in the frequency range of 800 MHz–3 GHz, and less than 0.5% of a wavelength in air at frequencies below 800 MHz.

6. SAR measurement protocols

6.1 Introduction

RF exposure conditions experienced by handset users are in the near-field of the device, where small changes in operating conditions and device positions may result in significant variations in SAR. For example, small variations of the following parameters generally result in significant SAR variations (Kuster [B90]):