HUMAN HEAD PHANTOMS FOR COMPLIANCE AND COMMUNICATION PERFORMANCE TESTING OF MOBILE TELECOMMUNICATIONS EQUIPMENT AT 900 MHz

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ABSTRACT

A new head phantom has been introduced by various standardization commissions for compliance testing of handheld mobile telecommunications equipment as well as for radiated RF power performance. This Specific Anthropomorphic Mannequin (SAM) is compared to the Generic Head Phantom and three high resolution anatomical head models with respect to the SAR evaluation of mobile phones. The test device used was a generic mobile phone equipped with different antenna types operating at 900 MHz as well as a commercially available multi-band phone. The spatial peak SAR values averaged over 1 g and 10 g as well as the radiation patterns have been evaluated using simulations for all test positions. The values for SAM and the Generic Head Phantom have been verified by experimental means. The results confirm that the use of the SAM phantom filled with the proposed tissue simulating liquid constitutes a conservative approach with respect to the maximum user exposure.

INTRODUCTION

In the past, numerous human head models have been proposed for use in the compliance testing of mobile telecommunications equipment (MTE) with safety standards. Head phantoms both for the numerical and for the experimental assessment of the specific absorption rate (SAR) have been suggested by different research groups. Since the possible health risks of mobile phones are becoming more and more an issue of liability, the mobile phone industry as well as several governmental regulatory bodies have emphasized the need for a standardized procedure for the compliance testing of MTE which meets the highest requirements with respect to accuracy and repeatability. It is obvious that a human head model which is well defined in terms of shape and dielectric parameters represents the cornerstone of any testing procedure [1], [2], [3], [4], [5], [6]. Several working groups are currently in the process of standardizing phantoms for antenna performance tests [7] and [8].

OBJECTIVES

The objectives of this paper are to provide quantitative indications about the margin of exposure to actual human anatomies as well as to compare the Generic Head Phantom with SAM at 900 MHz. In addition SAM shall be evaluated with respect to radiation performance assessments.

BASIC PHANTOM REQUIREMENTS

The basic requirements for phantoms used in the compliance testing procedures of handheld devices have been outlined in [9] and were basically adopted by [5]:

- 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 usage of wireless handsets.
- The test results shall not unnecessarily overestimate the peak SAR expected in actual users in order to prevent unnecessary inhibition of the advancement of new mobile communications technologies.
- The phantom shall enable high repeatability, allow stable and repeatable device positioning for peak SAR measurements and be effective for verifying repeatability and reproducibility among inter-laboratory comparisons.
- The phantom shall be practical for routine compliance testing.

- The phantom shall satisfy these criteria for contemporary and future handset designs and be unbiased with respect to any particular handset design or shape, i.e., handset designs that produce lower assessed SAR values should correspondingly result in reduced exposure in real-world situations, and vice-versa.

The criteria for phantoms used for communication performance testing are less obvious, except for provision of excellent reproducibility. Possible choices are representation of an average or a worst-case user. In contrast to SAR, radiation characteristics may also be significantly influenced by the shoulders.

DEVELOPED STANDARD PHANTOMS

A series of studies have been conducted to evaluate the dependence of the absorption upon internal anatomy, head size and shape (adult vs child), tissue parameters, phone, accessories, etc. [10], [11], [12], [13], [14], [15], [16], [17]. Based on these studies, it can be conclusively derived that a conservative approach is achieved if the phantom satisfies the following requirements:

- The H-field generated by the handset at the interface shell/head-tissue simulating liquid is higher or equal to the H-field generated at the skin of any user during intended operation of the phone. In other words, the separation between phone and tissue simulating liquid should be equal or smaller than in the real world.
- The head-tissue simulating liquid (HSL) results in higher absorption than any head tissue combinations [14].

Two phantoms have been developed in order to meet these requirements:

- The first phantom developed was the Generic Head Phantom (Figure 1). Its shape in the ear region was taken from measurements of 52 adult volunteers (male and female). It was designed in such a way that the distance between the mobile phone and the phantom surface would always be smaller than for 90 % of the people investigated. The physical phantom shell is constructed of Ureol ($\epsilon_r = 3.7$) with a thickness of 2.7 mm. It is filled with brain tissue simulating liquid, the parameters of which are $\epsilon_r = 41.0$ and & $\sigma = 0.85$ S/m at 900 MHz. The ear of the Generic Head Phantom is represented by a lossless spacer with a radius of 15 mm and a thickness of 2 mm, positioned at the location of the opening of the auditory canal. This leads to an overall shell thickness of 4.7 mm in the ear region. This phantom served as a quasi-standard for the compliance testing of MTE until the end of 2001. A detailed description of the Generic Head Phantom can be found in [9].
- In order to maximize consumer trust in compliance testing procedures, the Standardization Coordinating Committee 34 of IEEE (SCC34-SC2) recognized the necessity to base the phantom on a larger survey of human heads [18]. Consequently, it developed and proposed the Specific Anthropomorphic Mannequin (SAM). The shape of SAM, shown in Figure 1, corresponds to the 90^{th} percentile of the data for the adult male head. The thickness of the shell was selected as lossless and as thin as technically feasible, i.e., 2 mm. At the ear reference point, the thickness is increased to 6 mm (average thickness of the compressed ear). The ear itself is shaped in such a way to permit accurate and repeatable positioning of the phone under test. The dielectric parameters of the tissue simulating liquid for SAM were derived from worst-case considerations [14] and are $\epsilon_r = 41.5$ and $\sigma = 0.97$ S/m at 900 MHz.

The SAM phantom has also been adopted by CENELEC [2] as well as IEC [19] and ARIB [4] for the compliance testing of handheld phones. Lacking better criteria, CTIA has further proposed the use of SAM for radiated power and RF receiver performance tests [7].

HIGH RESOLUTION ANATOMICAL HUMAN HEAD MODELS

The spatial peak SAR and the radiation patterns obtained by the two homogeneous phantoms were compared with those of the following high resolution anatomical human models:

- *Adult Female:* The female head phantom (HR-EF-1) was generated from magnetic resonance images (MRI) taken of a 40 year old European female volunteer. During the MRI scan both ears were slightly compressed against the surface of the head in order to simulate the correct shape of the pinna while using a mobile phone. The MRI data consist of 121 different slices (Figure 1). In the ear region, the slices have a thickness of 1 mm; all other slices have a thickness of 3 mm. The high resolution of the ear region allows the accurate representation of the pinna as well as the anatomical details of the inner ear. 15 different tissues were distinguished.

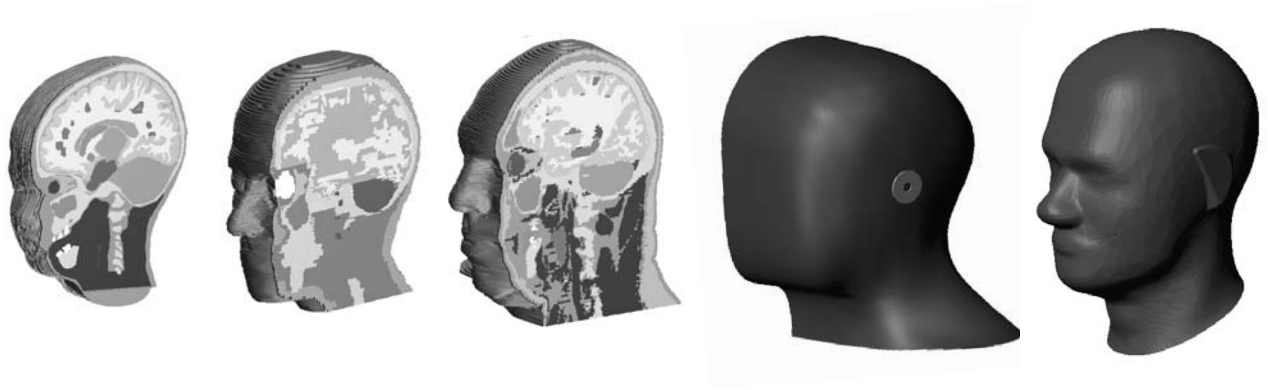

Figure 1: Phantoms (from left to right): child phantom (age 3), female head phantom (HR-EF-1), male head (based on data set of visible human project), Generic Head Phantom, Specific Anthropomorphic Mannequin (SAM)
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- *Adult Male:* This male phantom is based on the data set generated by the visible human project. The axial slice distance is 2 mm (facet tolerance X-Y: <0.2mm), whereby more than 100 different tissue/organ types are distinguished. Since the fat content of the person is high, fat parameters have been assigned to all connective tissues.
- *Child of Age Three:* An MRI data set of a three-year old child could be obtained. The horizonal slices (facet tolerance X-Y: < 0.2mm) had a sagital slice distance of 1.1 mm, whereby 32 tissues were distinguished.

At least the skin, muscle, fat, bone, CSF, grey and white brain matter, blood, cartilage, vitreous humour, lens and eye sclera were distinguished in all models. The same parameters of [20] were assigned independent of age. The resulting human head models in the SEMCAD compound format are tissue/organ based 3D CAD representations which are much more accurate and flexible than voxel descriptions.

PHONES

For this study, the exposure from three phones has been compared. Two of the phones are composed of an electrically and geometrically well defined generic mobile phone (GMP) equipped with two different antennas. The different GMP are based on the same metallic box (140x40x16 mm) which has a plexiglas coating ($\epsilon_r = 3.7$) on the side which faces the cheek of the phantom head (Figure 2). The ear reference point (loudspeaker position) is assumed to be centered 10 mm below the top of the phone. Unwanted surface currents on the feeding cable were reduced by integrating a tuned stub into the case of the phone at the input connector and by placing ferrites around the feeding cable. The third phone is a commercially available tri-band phone.

- *GMP-M900:* The generic mobile phone equipped with a 900 MHz $\lambda/4$ monopole antenna, 80 mm length, 1.2 mm radius.
- *GMP-H900:* The generic mobile phone equipped with a 900 MHz helical antenna, 6.5 mm diameter, 7 turns with 7° pitch angle, 0.6 mm wire radius.
- *T250*: The T250 is a commercially available tri-band phone (GSM, DCS, PCS) of Motorola Inc. The CAD data set was provided by the manufacturer, and a sample was purchased for measurements.

EXPOSURE POSITIONS

In this study, only the two standard positions were evaluated for left-hand usage. Due to the antenna positions, it can be expected that the maximum exposures occur on the left side of the phantom. In all cases, the phone was rotated such that the line connecting the speaker and microphone coincided with the plane through the ear canal/ear reference point and the mouth (reference plane). The ear reference point was defined for the Generic Head Phantom as well as for SAM. For the anatomical adult heads, the reference points were defined as located on this reference plane but 15 mm above and behind the ear canal (position of best acoustic coupling [5]). For the child, the shift was reduced proportionally to the different sizes of the ear, i.e., to 11 mm. The phone was then rotated around its acoustic output until it was planar to the ear lobe and touching the face.

Figure 2: Phones (from left to right): GMP-M900, GMP-H900, T250.

This position is referred as "touch". The "tilted" position is a rotation of 15° around the axis normal to the reference plane at the ear reference point in all cases except the Generic Phantom for which the absolute angle is 100° [1]. Only left-handed usage was evaluated since maximum exposure is expected on the left side.

METHOD

All simulations were performed with SEMCAD, and the experimental validations were performed using DASY3, both of which are products of Schmid & Partner Engineering AG, Zurich (see Section Validation). The simulation platform SEMCAD is based on the FDTD method and was jointly developed by the Institute for Integrated Systems (IIS), the Foundation for Research on Information Technologies in Society (IT'IS) and industrial partners. SEMCAD provides all state of the art features required for numerical dosimetry. In addition, it integrates a CAD environment which enables the free positioning, moving and tilting of the head phantom models, without the restrictions normally posed by predefined mesh or pre-voxeled head models. Nonuniform meshes can be generated automatically, according to the requirements of the geometry.

In order to minimize uncertainties due to staircasing effects with the conducting structures, the phone model is always oriented along the grid axes and the head phantoms are tilted instead. The phantoms were discretized in different nonuniform meshes with grid steps between 0.3 mm and 10 mm in free space. In a series of simulations, the required grid resolution was determined such that discretization influences on the numerical results could be excluded. Inside the phantoms, the grid step was reduced to be less than $\lambda/10$. In the ear regions of the phantom the maximum grid step was additionally limited to 0.3 mm - 0.5 mm. This enables the correct representation of the phantom shell and minimizes the numerical errors at the location where the SAR maximum is expected. The overall grid dimensions were $390 \times 330 \times 550\,\mathrm{mm}^3$. Depending on the phone position and head model, between five and ten million grid cells were required for the simulations. The calculation domain was truncated with PML absorbing boundary conditions.

The post-processor also supports the evaluation of spatial peak SAR. The implemented algorithms are compliant with the procedure defined in [5], i.e., each voxel is considered to be the center of a cubical volume which is expanded until the required averaging mass is reached within $\pm 0.1\,\%$. If a surface of an averaging volume expands beyond the outermost surface of the model, its center voxel will be disregarded for the further averaging process. This voxel will be assigned the highest value of those averaging volumes which include it.

The helical antenna is simulated with a novel subgrid algorithm based on cubical spline interpolation [21]. The algorithm allows a local mesh step refinement of 1:2. Thus, the helix is discretized with a mesh step size of 0.3 mm, which is a quarter of its wire diameter. The application of the subgrid algorithm therefore allows very accurate prediction of the fields around the antenna.

RESULTS

The results for the maximum 1 g and 10 g averaged spatial peak SAR values obtained from the tested positions are summarized in Figure 4. All values were normalized to those of SAM (100%). The absorption in the ear pinna of all anatomical human phantoms was not considered in the averaging process. The radiation patterns are compared in Figure 5. The following conclusions can be drawn:

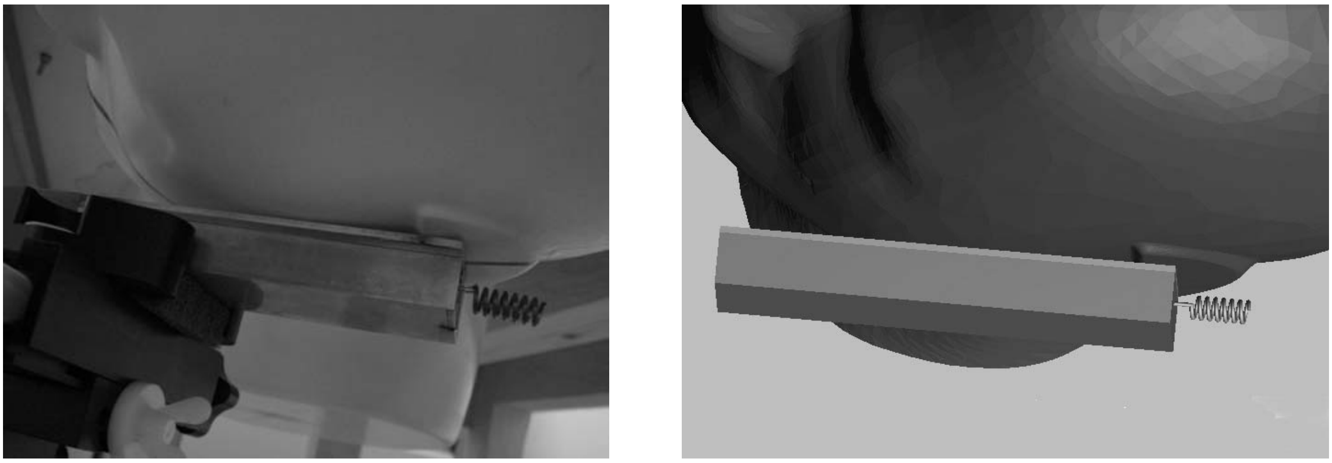

Figure 3: Measurement setup (left) and numerical model (right) of the SAM Phantom with the generic mobile phone in the "touch" position. The differences in the region of the phantom chin are due to the different focal widths of the camera of the CAD system and the real camera.

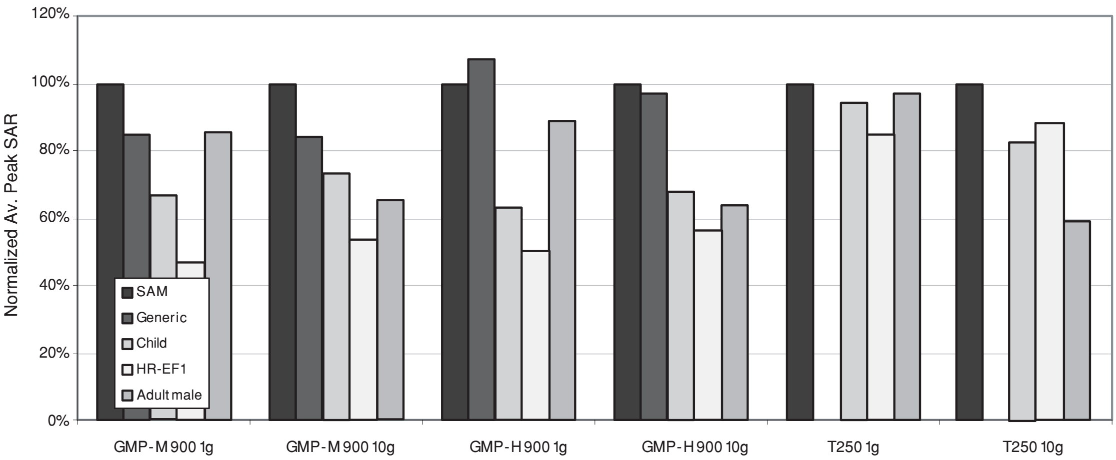

Figure 4: Comparison of the maximum spatial peak SAR obtained by the different phantoms in the two tested positions, whereby all results were normalized to the spatial peak SAR assessed for SAM.

- For the positions evaluated, SAM always provided the highest spatial peak SAR. It must be noted that the ear of the adult female was strongly pressed, i.e., to only 4 mm thickness; the pinna of the ear of the adult male was cut to 6 mm, and the child's face length and ear thickness corresponded to that of age 3.
- In the "touch" position, the overestimation is relatively small if the peak SAR is induced at the location of the display or keyboard. These cases require more detailed study and discussion.
- In addition, the results confirm that the exposure of children and adults is similar. All differences can be explained by different distances of current densities from the tissue and the different tissue compositions.
- For far-field evaluations, SAM provides reasonable worst-case radiation patterns.

VALIDATION

The simulations were extensively validated by measurements with SAM as well as with the Generic Head Phantom of Schmid & Partner Engineering AG. The measurement data were obtained with the DASY3 near-field scanner, which is the successor of the dosimetric assessment system described in [22]; DASY3 provides enhanced precision regarding isotropy, sensitivity and spatial resolution and permits more flexible probe positioning over a larger scan area. The measurements were conducted according to the latest guidelines for

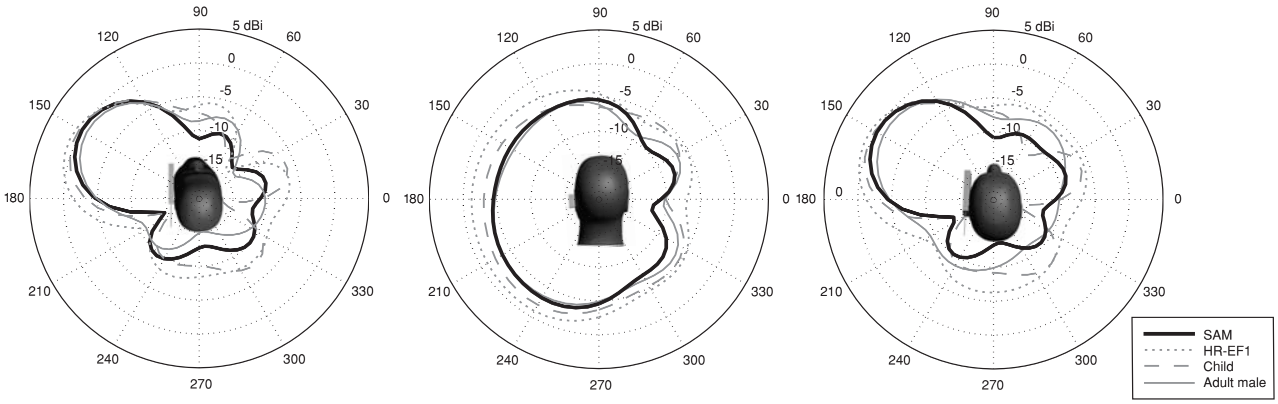

Figure 5: Radiation pattern of the GMP-M900 in the "touch" position for the different phantoms. *left:* plane of the antenna axis; *middle:* plane normal to the antenna axis; *right:* plane normal to the body axis.

compliance testing [5]. The measurement uncertainty for these evaluations was determined to be 26.8 % for DASY3 according to the procedure described in Section 6 of the same standard.

The deviation was generally less than 12% although larger in some cases (maximum 23%). However, where large deviations occurred, we also observed large differences in the feedpoint impedance, which accounts for some of the differences [10]. In summary, the agreement between measured and simulated results is within the uncertainties of the applied methods for spatial peak SAR assessments.

CONCLUSIONS AND OUTLOOK

Within the bounds of this study, the exposure values assessed with SAM following the protocol as defined in [2] and [5] were compared to those of several anatomical head models as well as of the Generic Head Phantom. Three different phones were evaluated in the "touch" and "tilted" positions on the left side of the phantom. The simulation results of the homogeneous head models could be validated by measurements.

Compared to the original method for MTE compliance testing based on the Generic Head Phantom, the SAM phantom and the new liquid parameters based on worst-case considerations represent a more conservative approach. The study confirmed that SAM provides a conservative estimate for the investigated positions. However, additional studies are necessary in order to settle this issue completely:

- evaluation of additional positions at the anatomical heads in order to confirm corresponding results for all positions within the range of intended usage of the phones
- extension of the study to cover the entire frequency range of interest
- evaluation of the effect of variations in tissue parameters
- evaluation of the spatial peak SAR in the pinna of the ear only
- assessment of the maximum local temperature increase in children and adults

A precondition for obtaining comparable results from studies of different laboratories is better standardization of the tissue parameters.

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