# Inaccuracies of a Plastic "Pinna" SAM for SAR Testing of Cellular Telephones Against IEEE and ICNIRP Safety Guidelines

Om P. Gandhi, *Life Fellow, IEEE,* and Gang Kang*, Senior Member, IEEE*

***Abstract*—A 2-mm-thick plastic shell with 5–10-mm-thick tapered plastic spacer in the shape of a "pinna"-specific anthropomorphic mannequin (SAM) head model is being used for determination of the specific absorption rate (SAR) of cellular telephones for compliance testing against IEEE and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) Safety Guidelines used in the U.S. and Europe, respectively. We have used three-dimensional computer-aided design files of the SAM Model with 1-mm resolution to calculate peak 1- and 10-g SAR for "cheek" and "15°-tilted" positions of some typical telephones for comparison with those for three anatomic models of the head to show that the SAR obtained for SAM is up to two or more times smaller than for anatomic models. This is due to the shift of the high SAR locations to a low radiated fields region away from the antenna, particularly at 835 MHz, and a substantial physical separation from the absorptive phantom at 1900 MHz. Due to the use of lossless plastic for the "pinna," another handicap of the SAM model is the total lack of knowledge of 1- or 10-g SAR in the pinna tissues required by all safety guidelines (current or proposed). To remedy this situation, we propose a modified SAM with a lossy "pinna," for which 1- and 10-g SARs are relatively close to those for anatomic models, provided we use a fluid of higher conductivity than that currently used for compliance testing at 835 MHz. Lastly, we compare the implications of the current IEEE and ICNIRP guidelines and the newly proposed IEEE guidelines with a relaxed limit of 4.0 W/kg for any 10-g of tissue of the pinna for maximum allowable powers for cellular telephones at 835 and 1900 MHz to show that the newly proposed relaxed IEEE limits will allow radiated powers that may be 8–16 times those permitted by the current IEEE Standard and up to two times higher than those permitted under ICNIRP guidelines used in over 30 countries.**

***Index Terms*—Comparison of specific absorption rate (SAR) obtained for specific anthropomorphic mannequin (SAM) and anatomic models, considerably lower SAR for SAM, accurate SAR obtained with a proposed modified SAM.**

## I. Introduction

WE HAVE previously pointed out that a 6-mm-thick smooth plastic "pinna" model would result in a measured or calculated peak 1- or 10-g specific absorption rate (SAR) that may be up to two or more times smaller than realistic anatomic models for SAR compliance testing against IEEE or International Commission on Non-Ionizing Radiation Protection (ICNIRP) safety guidelines, respectively [1]. This is on account of an artificial separation of several millimeters caused by the plastic spacer in the shape of pinna from energy absorbing tissue-simulant phantom. Whereas the Utah model of the human head with a pinna replaced by an insulting dielectric was used for previous calculations, the three-dimensional (3-D) computer-aided design (CAD) files of the specific anthropomorphic mannequin (SAM) head model proposed for SAR compliance testing both in North America and Europe are currently available and are used in this paper for comparison of the calculated 1- and 10-g SARs for some typical telephones against the corresponding SARs calculated for some lossy ear anatomic models of the human head. Using the well-established finite-difference time-domain (FDTD) method, the peak 1- and 10-g SARs are calculated both for the "cheek" and "15°-tilted" positions of the handsets for both the plastic-ear SAM and a couple of anatomic models; namely, the Utah model and the "Visible Man" model using a resolution of $1 \times 1 \times 1$ mm for each of the head models. It is shown that because of the 5–10-mm physical separation of the cellular telephone from the lossy phantom used for the SAM model by means of a plastic, this model used as a SAR Compliance Standard both in Europe and the U.S. underestimates the peak 1- and 10-g SAR by a factor on the order of 1.6–2.0 or more, as compared to the SAR obtained with anatomic models. Another disadvantage of the SAM model is the total lack of determination of the SAR in the pinna, which, in this model, is replaced by a nonabsorptive plastic spacer. It should be recognized that both the IEEE and ICNIRP Standards do require determination of the SAR in all of the tissues of the head including the pinna even though there is a move in the newly proposed IEEE Draft Standard [6] to relax the SAR limit for the pinna from 1.6 W/kg for any 1-g of tissue to 4.0 W/kg for any 10-g of tissue of the pinna.

In this paper, we also compare the implications of using ICNIRP, and the current and proposed IEEE standards for SAR compliance testing of cellular telephones [2]–[6]. Using typical handset dimensions and commonly used monopole and helical antennas, it is shown that the current IEEE standard of peak 1.6 W/kg for any 1 g of tissue is the most conservative, and the proposed IEEE standard [6], if approved, would be the least conservative, allowing radiated power levels that would be 8–16 times higher than the current IEEE C95.1 Safety Guide-

Manuscript received November 21, 2003; revised February 10, 2004.

O. P. Gandhi is with the Electrical and Computer Engineering Department, University of Utah, Salt Lake City, UT 84112 USA (e-mail: gandhi@ece.utah.edu).

G. Kang was with the Electrical and Computer Engineering Department, University of Utah, Salt Lake City, UT 84112 USA. He is now with the Electrical Engineering Department, Duke University, Durham, NC 27517 USA (e-mail: gkang@ee.duke.edu).

Digital Object Identifier 10.1109/TMTT.2004.832689

TABLE I
COMPARISON OF PEAK 1- AND 10-g SARS OBTAINED FOR SAM AND ANATOMIC MODELS FOR THE “CHEEK” AND “15°-TILTED” POSITIONS OF THE $22 \times 42 \times 122$ mm HANDSETS WITH DIFFERENT ANTENNAS. THE SARS ARE NORMALIZED TO A RADIATED POWER OF 600 mW AT 835 MHz. GIVEN IN THE LAST COLUMN ARE THE SARS FOR A PROPOSED MODIFIED SAM WITH LOSSY PINNA IN BETTER AGREEMENT WITH ANATOMIC MODELS

| | Antenna Axial Length mm | **Peak 1-g SAR (W/kg)** | | | | |
|---|---|---|---|---|---|---|
| | | SAM[1] 5-10 mm plastic pinna | Utah Model, 6 mm-thick pinna | Utah Model, 14 mm-thick pinna | Visible Man, 6 mm-thick pinna | Modified SAM[2], 4 mm lossy pinna (2 mm shell) |
| Cheek Position | 80 mm monopole | **3.30 (3.40)** | 10.82 | 9.58 | 6.43 | **6.90 (4.97)** |
| | 20 mm helix | **4.18 (4.33)** | 14.40 | 14.51 | 9.07 | **9.16 (6.44)** |
| 15°-Tilted position | 80 mm monopole | **2.49 (2.80)** | 10.90 | 8.80 | 7.12 | **6.43 (4.73)** |
| | 20 mm helix | **2.65 (2.98)** | 14.96 | 12.96 | 9.95 | **7.72 (5.53)** |
| | | **Peak 10-g SAR (W/kg)** | | | | |
| Cheek Position | 80 mm monopole | **2.36 (2.40)** | 3.67 | 4.55 | 2.34 | **3.64 (2.95)** |
| | 20 mm helix | **3.03 (3.13)** | 4.79 | 6.61 | 3.21 | **4.61 (3.65)** |
| 15°-Tilted position | 80 mm monopole | **1.69 (1.88)** | 3.83 | 4.46 | 3.17 | **4.07 (3.25)** |
| | 20 mm helix | **1.77 (1.91)** | 5.06 | 5.94 | 4.15 | **4.30 (3.28)** |

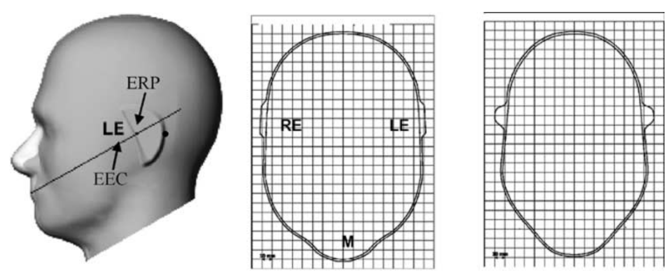
[1] Used for the calculations is the pinna spacer and plastic shell of $\varepsilon_r = 2.56$. Also shown in parentheses are the SARs calculated for $\varepsilon_r = 4.0$ for the plastic shell and pinna spacer.

[2] Assumed for these calculations is a higher conductivity $\sigma = 1.4$ S/m at 835 MHz (given in parentheses are the lower values obtained for $\sigma = 0.9$ S/m fluid presently used for the tissue-simulant phantom for SAM). $\varepsilon_r = 41.5$ for each of the cases of modified SAM.

lines [3] and 3–5 times higher than ICNIRP guidelines [5], particularly if the SAR measurement for the pinna is ignored as currently done with SAM [2], [3].

We are aware of publications claiming that the use of plastic-ear SAM-like models result in a conservative estimate of the peak 1- and 10-g SAR [7], [8], yet both of these publications show the highest SAR measured for such models at 800–900 MHz to be 3–4 cm below the base of the antenna in the cheek region. This is not the region of the highest electric or magnetic fields emanating from the monopole. In this paper, we focus on the visualization of the peak 1- and 10-g SAR regions obtained for SAM vis à vis the anatomic models and find that consistent with [7], [8] use of a plastic spacer for SAM results in shifting the high SAR locations to the regions of low radiated fields away from the antenna, particularly at 835 MHz, while this effect does not occur for anatomic models where the highest SAR region is always close to the base of the antenna, i.e., for the lossy pinna and the head tissues behind it [9], [10].

To remedy this high degree of underestimation of SAR, we propose that the plastic spacer of SAM be replaced by a lossy tissue-simulant fluid of depth 4 mm of the same shape as the “pinna” for this model with an external shell thickness of only 2 mm as for the rest of SAM. Due to the similarity of this modified SAM to reality, the peak 1- and 10-g SARs with this lossy-ear phantom are in much better agreement within (±15%) of those obtained for the anatomic models of the head, particularly at 1900 MHz. At 835 MHz, the SARs for this lossy pinna SAM are still considerably lower than those of the anatomic models (see the last column of Table I for the numbers in parentheses). Therefore, we suggest use of a higher conductivity fluid than that used currently for safety compliance testing to obtain a better agreement with the SARs obtained for anatomic models (see Table I).




a. Side view.
b. Cross-sectional cut through reference plane R passing through mouth (M).
c. A cut 30 mm below plane R.

Fig. 1. SAM head model with three cross-sectional cuts defining the 5–10-mm thickness of the plastic shell for different cross sectional planes [3]. Also shown are the entrance to ear canal (EEC) and the ERPs. Rather than the EEC, the ERP is recommended by the standard for placement of the acoustic output of the handset against the SAM.

a. The Utah Model
b. The "Visible Man" Model.
c. Utah Model with thinner ear – left-Back view.

Fig. 2. Visualization of the three anatomically based models of the head.

TABLE II
COMPARISON OF PEAK 1- AND 10-g SARs OBTAINED FOR SAM AND ANATOMIC MODELS FOR THE "CHEEK" AND "15°-TILTED" POSITIONS OF THE $22 \times 42 \times 122$ mm HANDSETS WITH DIFFERENT ANTENNAS. THE SARs ARE NORMALIZED TO A RADIATED POWER OF 125 mW AT 1900 MHz. GIVEN IN THE LAST COLUMN ARE THE SARs FOR THE PROPOSED MODIFIED SAM WITH LOSSY PINNA IN BETTER AGREEMENT WITH ANATOMIC MODELS

| | Antenna Axial Length mm | Peak 1-g SAR (W/kg) | | | | |
|---|---|---|---|---|---|---|
| | | SAM[1] 5-10 mm plastic pinna | Utah Model, 6 mm-thick pinna | Utah Model, 14 mm-thick pinna | Visible Man, 6 mm-thick pinna | Modified SAM, 4 mm lossy pinna (2 mm shell) |
| Cheek Position | 40 mm monopole | **0.73 (0.82)** | 2.05 | 2.31 | 1.97 | **2.15** |
| | 20 mm helix | **0.93 (1.05)** | 2.24 | 2.54 | 2.66 | **2.69** |
| 15°-Tilted position | 40 mm monopole | **1.13 (1.27)** | 3.06 | 3.00 | 3.06 | **2.44** |
| | 20 mm helix | **1.30 (1.48)** | 3.52 | 3.45 | 3.96 | **2.91** |
| | | Peak 10-g SAR (W/kg) | | | | |
| Cheek Position | 40 mm monopole | **0.49 (0.51)** | 0.85 | 1.04 | 0.90 | **1.06** |
| | 20 mm helix | **0.59 (0.62)** | 0.94 | 1.16 | 1.02 | **1.24** |
| 15°-Tilted position | 40 mm monopole | **0.74 (0.79)** | 1.16 | 1.33 | 1.36 | **1.48** |
| | 20 mm helix | **0.82 (0.88)** | 1.34 | 1.52 | 1.61 | **1.65** |

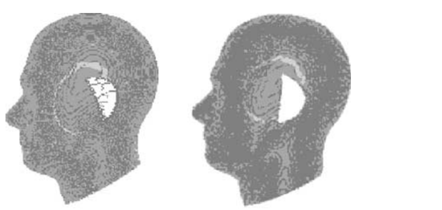
[1] Used for the calculations is the pinna spacer and plastic shell of $\varepsilon_r = 2.56$. Also shown in parentheses are the SARs calculated for $\varepsilon_r = 4.0$ for the plastic shell and pinna spacer.

## II. MODELS OF THE HEAD

For studies reported in this paper, we have used the SAM model with plastic "ear" shown in Fig. 1(a). This model with 2-mm plastic-shell thickness and an "integral ear spacer" of an additional 3–8-mm thickness and dielectric constant less than five and loss tangent less than 0.05 is recommended for SAR compliance testing both in Europe and the U.S. [2], [3]. This model for which the external and internal surface profiles were provided courtesy of Dr. B. Beard, U.S. Food and Drug Administration, was digitized to form a 3-D model with resolution of $1 \times 1 \times 1$ mm. As seen for a couple of cross sections of this model [see Fig. 1(b) and (c)], the thickness of the plastic shell can vary from 5 to 10 mm or more. Assumed for the calculations was dielectric constant $\varepsilon_r = 2.56$ or 4.0 for the plastic shell (conductivity $\sigma = 0$) and that the model is filled with a homogeneous lossy medium of dielectric properties suggested in the European Committee for Electrotechnical Standardization (CENELEC) and IEEE Compliance Standards [2], [3]. These properties for the tissue-simulant media are $\varepsilon_r = 41.5$, $\sigma = 0.90$ S/m for 835 MHz, and $\varepsilon_r = 40.0$ and $\sigma = 1.40$ S/m at 1900 MHz.

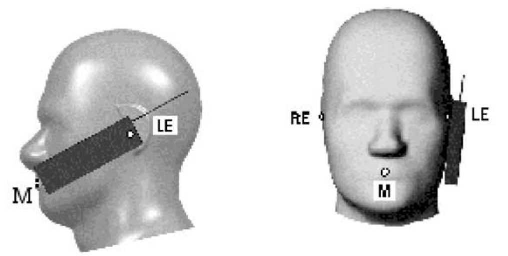
Also used for peak 1- and 10-g SARs were two anatomic models; namely, the Utah model and the "Visible Man" model. Both of these models, described in detail in an earlier paper [1], are classified into various tissues e.g., brain, fat, bone, cartilage, etc. with voxel resolution of $1 \times 1 \times 1$ mm$^3$. A visualization of the two anatomic models used for comparison studies is given as Fig. 2(a) and (b), respectively. Whereas the Utah model was obtained from the magnetic resonance imaging (MRI) scans of a male volunteer of 64-kg weight and 176.4-cm height [10], the "Visible Man" model was segmented by Ziriax and Mason (personal communication) from the MRI scans of the cadaver of a husky 105-kg individual. Even though the weights of the heads of the two models are within 10% of each other (5406 against 5949 g), the weights of the various tissues are considerably different and are given by Gandhi and Kang in [1]. Most notably, the amount of fat in the "Visible Man" model is considerably higher (1010 versus 685 g), and brain is somewhat smaller (1134.5 versus 1501.2 g) and the pinna for the "Visible Man" model is much thinner, i.e., 6 versus 14 mm for the Utah model. To understand the role that the thickness of pinna may play in comparing the SARs with those of SAM, we have reduced the thickness of the voxels associated with the pinna of the Utah model by a factor 6/14 and reattached it back to the model of the head. This manipulation allows us to create yet another version of the Utah anatomic model, shown in Fig. 2(c), where the thickness of the pinna is 6 mm instead of the original 14-mm-thick pinna for this model.

As seen in Tables I and II, the peak 1- and 10-g SARs obtained for SAM are considerably lower than those for the three above-defined anatomic models by a factor of up to two or more for some of the telephones of handset and antenna dimensions that are typical of today's devices. Since this is primarily on account of totally ignoring the pinna SAR by the plastic-ear SAM, we have considered a modified version of SAM where the so-called "integral ear spacer" of SAM is assumed to be filled with the lossy tissue-simulant fluid instead of a lossless dielectric, except that there is a 2-mm-thick plastic shell that is assumed to be the container of the fluid for this, as well as for the rest of the model of the head (shown in Fig. 1). In developing this modified SAM [see Fig. 3(b)], another change made is to rotate the "pinna" by 24° so that it connects to the cheek in a more natural fashion rather than the artificial angle that is recommended for the current plastic-ear SAM. Thus, the modified SAM developed is shown in Fig. 3(b), where the placement of the lossy ear may be compared with the abnormal angle used for the dielectric ear SAM of Fig. 1(a) or Fig. 3(a).



(a) (b)

Fig. 3. (a) Original plastic-ear SAM. (b) Proposed lossy-ear SAM. In addition to using lossy tissue-simulant dielectric properties, the "ear" is rotated by 24° to have a more natural appearance of the "ear" vis à vis the cheek.




a. Cheek position – side view.

b. Cheek position – front view.

c. 15°-tilted position – front view.

d. 15°-tilted position – top view.

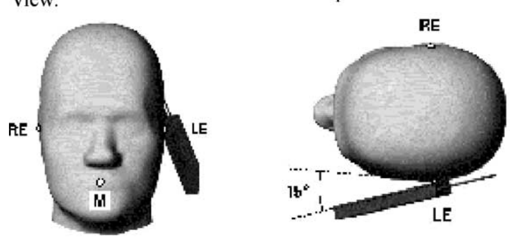
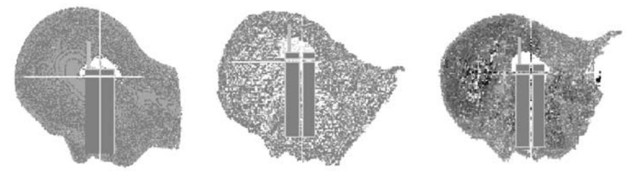



Fig. 4. Placement of a radiating handset for cheek and 15°-tilted positions relative to plastic-ear SAM [3].

## III. Orientations and Telephones Used for SAR Calculations

The method used for calculation of the SAR distributions is the well-established FDTD method. This method described in several texts (e.g., Taflove [12] and Taflove and Hagness [13]) has been used successfully by various researchers [1], [9]–[11], [14], [15] and, therefore, would not be described here in any detail. As required by the SAR Compliance Standards [2], [3], two orientations of the selected telephones; namely, the cheek position and 15°-tilted position, have been used for the SAR calculations. As shown in Fig. 4(a) and (b) for the "cheek" position, the handset is placed such that the acoustic output point of the handset is placed against the ear reference point (ERP) [see also Figs. 1(a) and 5(a)]. While placed in this position, the handset is oriented such that the vertical centerline of the front face of the handset is in the plane passing through the three points marked as right ear (RE), left ear (LE), and mouth (M) on the SAM model [see Fig. 4(a)]. Thus, the handset placed is rotated in this plane such that the front of the handset touches the cheek of the model, as shown in Fig. 4(b). For the so-called "15°-tilted position," the telephone placed such that its centerline is in the reference plane $R$ passing through points RE, LE, and M [see Fig. 1(b)] is rotated away from the model by 15° [see Fig. 4(c)



a. SAM tilted forward by 62° and rotated towards the telephone by 5° for the handset to touch the cheek.

b Utah anatomic model of Fig. 2a tilted forward by 54° and rotated towards the telephone by 18° for the handset to touch the cheek.

c. "Visible Man" Anatomic Model of Fig. 2b tilted forward by 73° and rotated towards the telephone by 5° for the handset to touch the cheek.

Fig. 5. Tilted SAM and anatomic models used for SAR calculations for the "cheek" position with vertically placed telephones. As recommended in [3], the acoustic output point of the telephone is placed against the ERP of the SAM model (see Fig. 1).

and (d)]. As seen in Fig. 4(d), this has the effect of bringing the antenna somewhat closer to the head. The cheek and 15°-tilted orientations thus described are easy to use for the plastic-ear SAM and the lossy-ear modified SAM of Fig. 3(a) and (b), respectively. For the anatomic models of Fig. 2(a) and (b), the locations of the ear canals are well defined. Thus, the acoustic output point $P$ (assumed to be centrally located 1 cm below the top of the handset) is placed against the center of the entrance to the ear canal of the anatomic models, respectively.

Assumed for all of the SAR calculations is a handset of external dimensions $22 \times 42 \times 122$ mm, which is fairly typical of the cellular telephones in use today. This handset is represented by means of a metal box of dimensions $20 \times 40 \times 120$ mm, which is assumed to be covered with plastic of thickness 1 mm and dielectric constant $\varepsilon_r = 2.56$ ($\sigma = 0$) on all sides. It has previously been shown that the plastic-covered metal box representation is a fairly good representation of the handset that leads to peak 1-g SARs that are within 5%–10% of the values obtained using CAD files of the individual handsets [16], [17]. Used for the above handset are two different types of antennas; namely, the monopole and helical antennas for each of the frequencies i.e., 835 and 1900 MHz. Thus, we have used nominal quarter-wave monopole antennas of length 40 and 80 mm at 1900 and 835 MHz, respectively, as well as helical antennas of a total length of 20 mm at both frequencies. All of the antennas are assumed to be placed at the distal right-hand-side corner of the handset, which is also typical for most of the telephones in use today.

To avoid stair-step approximation for the plastic-covered metal box used to represent the handset, as well as for the antennas, we have tilted forward and rotated the SAM, as well as the anatomic models, so that the telephones may be placed vertically against them [see Fig. 5(a)–(c)] for the cheek-touch position. For our calculations, we have modeled the monopole antennas as a vertical stack of cells and the helical antennas using a procedure given by Lazzi and Gandhi [18]. For the current calculations, the helical antennas are modeled as a $2 \times 2$ stack of electric and magnetic sources with relative weights calculated using information obtained from analytical expressions for the far fields. This formulation has been shown to give computed results in very good agreement with experimental measurements for near-field, far fields, and the peak 1-g SAR [18].

For all of the results given in this paper, the peak 1- or 10-g SARs are calculated by taking averaging volumes in the shape of a cube, as prescribed in the IEEE Standard C95.3–2002 Annex E [19]. Both the ICNIRP and IEEE standards make no distinction between the tissues of the head or the pinna—hence, no distinction is made in calculating the peak 1- and 10-g SARs. For SAM, on the other hand, there is zero SAR for the pinna spacer made of a relatively lossless plastic and the 1- and 10-g SARs are calculated using the local SARs for the tissue-simulant fluid. It is recognized that, unlike the IEEE Standard C95.1 [4], the ICNIRP Standard [5] suggests a localized SAR averaging mass of 10 g of contiguous tissue. For near-field exposures such as those from cellular telephones, this mass is likely to be mostly at the surface. An averaging volume in the shape of a cube of 10-g mass has, nevertheless, been suggested in the CENELEC European Standard EN50361 [2] and has, therefore, been used for all the 10-g SARs given in this paper.

The newly proposed IEEE Draft Standard [6] would make a distinction between the tissues of the head and the pinna and allow higher SAR limits of 2 W/kg for any 10 g of tissues of the head (rather than the current limit of 1.6 W/kg for any 1 g of tissues) and an even higher SAR limit of 4 W/kg for any 10 g of tissues of the pinna. Furthermore, it suggests that tissues only of the head or the pinna be considered in determining the peak 10-g SARs and that the size of the cube be expanded so that 10 g of tissue ($\pm 5\%$) either of the head or pinna is contained within it for the purpose of determining the weight-averaged SAR. Since the purported purpose of this move is to harmonize the SAR safety limits with those of ICNIRP [5], it would be most informative to compare the implications of the three standards, i.e., the current IEEE Standard [4], ICNIRP guideline [5], and proposed IEEE Draft Standard [6] from the point-of-view of maximum radiated power allowed by the cellular telephones. This is done in Section VII.

## IV. Comparison of SARs Using SAM and Different Anatomic Models

Given in Tables I and II are the calculated peak 1- and 10-g SARs using the plastic-ear SAM and the three anatomic models, viz the two Utah models with pinna thicknesses of 14 and 6 mm, and the "Visible Man" model. Both the cheek and 15°-tilted positions have been considered for calculations of SARs for a typical handset of dimensions $22 \times 42 \times 122$ mm using either a monopole or a helix antenna. Used for calculations for the SAM model is the plastic shell and pinna spacer shown in Fig. 1 of dielectric constant $\varepsilon_r = 2.56$ or $4.0$, respectively. Shown in Figs. 6 and 7 are the locations of the peak 1- and 10-g SAR regions marked by dark squares for the SAM model and for the three anatomical models for some of the conditions of exposure given in Tables I and II, respectively. The salient features of results to note from Tables I and II and Figs. 6 and 7 are as follows.

1) Use of a 5–10-mm plastic "pinna" for SAM results in an underestimation of peak 1- and 10-g SAR by a factor of up to two or more, as compared to the anatomic models.

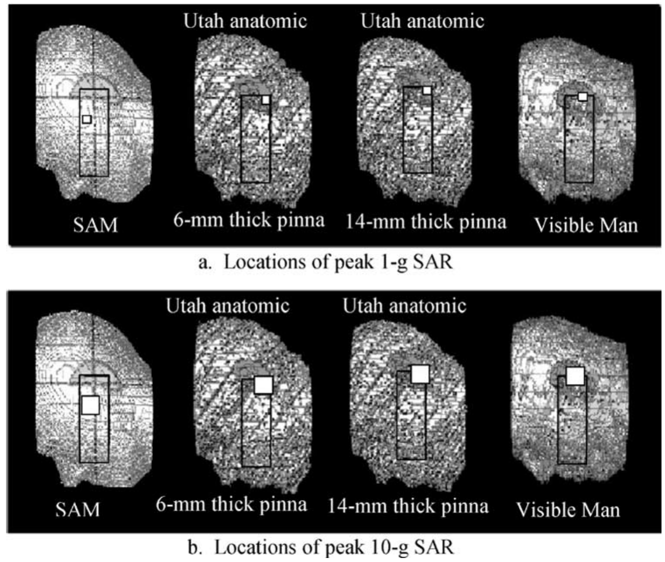



Fig. 6. Locations of the peak 1- and 10-g SAR regions (shown as white squares) for the SAM model and for three anatomical models for the "cheek" placement of the handset using a 20-mm-long helix antenna at 835 MHz. Whereas the peak 1- and 10-g SAR regions for the anatomic models include the lossy pinna, the highest SAR regions for the SAM model similar to [7] and [8] are considerably lower (by approximately 2.5 cm) in the cheek region.

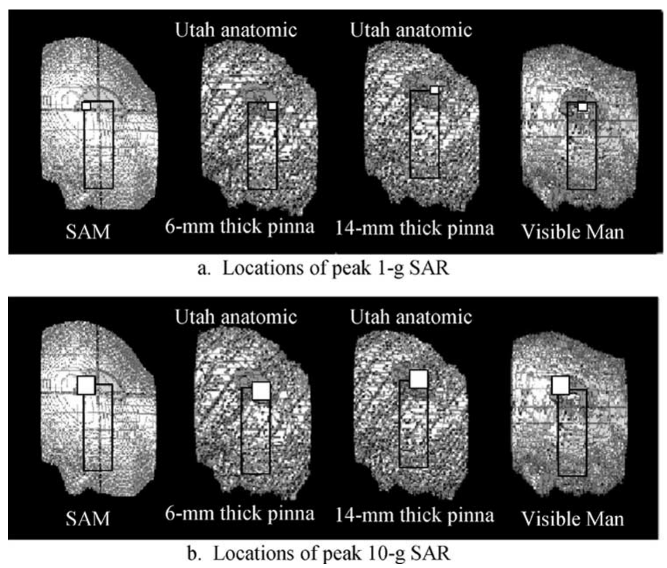



Fig. 7. Locations of the peak 1- and 10-g SAR regions (shown as white squares) for the SAM model and for three anatomical models for the "cheek" placement of the handset using a 40-mm-long monopole antenna at 1900 MHz.

In fact, the peak SAR location for SAM shifts to the cheek region approximately 2.5 cm below the base of the radiating antenna, particularly at 835 MHz, while the anatomic models invariably give peak SAR locations close to the base of the antenna or the top of the handsets (see Fig. 6). This observation of the shift of the peak 1- or 10-g SAR region away from the base of the antenna into the cheek region is in agreement with previously reported results for SAM or SAM-like models [7], [8]. Since this is not the region of the highest electric and magnetic fields emanating from the antenna, this is likely the reason why use of SAM results in greatly reduced 1- and 10-g SARs.

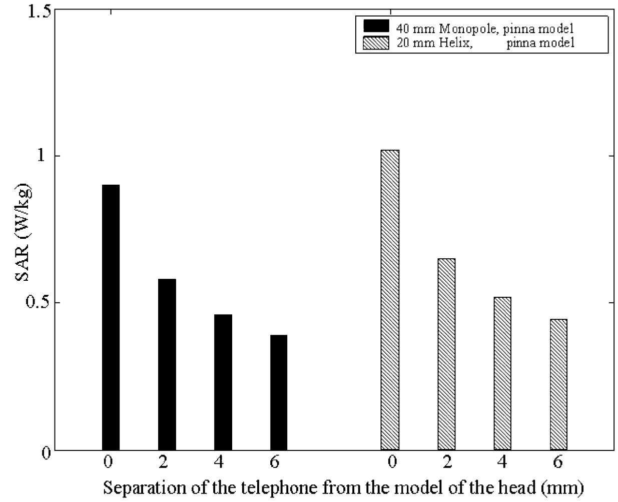
2) At 1900 MHz, the peak 1- and 10-g SAR region for SAM is behind the plastic spacer (see Fig. 7). However, since this region of the lossy phantom is 5–10 mm further from the radiating antenna because of the plastic spacer, the calculated 1- and 10-g SARs are up to a factor of two or more lower than those for anatomic models (see Table II). This point is discussed at length in Section V.
3) Use of a pinna spacer and plastic shell with a higher $\varepsilon_r$, say four, will result in slightly higher (up to 14%) peak 1- and 10-g SARs for SAM. This result is identical to that reported earlier [1] and is likely due to increased capacitive coupling of the electromagnetic (EM) fields from the cellular telephone to the lossy tissue-simulant medium used for SAM.

## V. Variation of SAR With Millimeter-Size Separations of the Telephones From the Head

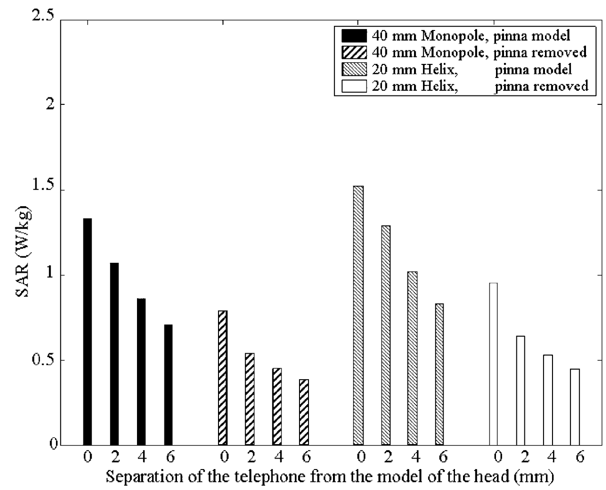
It is clear that the gross underestimation of both 1- and 10-g SARs obtained for SAM is likely due to a separation on the order of 5–10 mm provided by the plastic shell from the highly radiating antenna region of the handset to the lossy tissue-simulant fluid. This does not occur for the anatomic models when the telephone is pressed against the ear. In order to understand the role of the millimeter-size separations in reducing the SAR, we have used separations of 0, 2, 4, and 6 mm from the Utah and "Visible Man" models from the pinna to the front face of the telephone placed in the 15°-tilted position. The peak 10- and 1-g SARs thus obtained are given in Fig. 8(a)–(c), respectively. As reported earlier in the context of the planar or sphere phantoms [20], there is a monotonic decrease in both 1- and 10-g SARs for every 2-mm additional spacing of the radiator, i.e., the cellular telephone from the lossy tissues. This effect is demonstrated in Fig. 8(a)–(c) as to whether the anatomic models with or without pinna are used. Thus, it is no surprise that the SAM model with a plastic spacer of 5–10-mm thickness, as shown in Fig. 1, should result in an underestimation of peak 1- or 10-g SAR.

## VI. A Proposed Modified SAM With Lossy Pinna

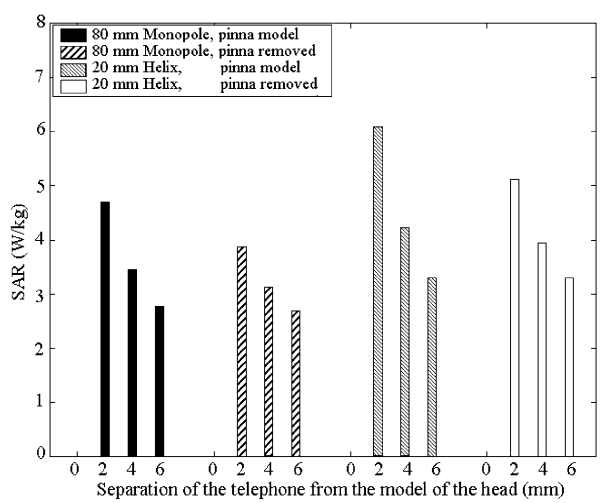
To remedy this high degree of underestimation of SAR for safety compliance testing, we propose that the plastic spacer of SAM in Fig. 1 be replaced by a lossy tissue-simulant fluid of 4-mm depth of the same shape as in Fig. 1(a) with an external shell of 2-mm thickness as for the rest of the SAM model. We also propose that this lossy pinna be placed relative to the cheek at a more natural angle for humans rather than the crooked angle that is used for the SAM model at the current time [see Fig. 1(a)]. Shown in Fig. 3(a) and (b) are the current plastic-ear SAM and proposed lossy-ear SAM side by side. For the proposed lossy-ear SAM, the "ear" is rotated by 24° to have a more natural appearance of the "ear" vis à vis the cheek. Given in the last columns of Tables I and II are the peak 1- and 10-g SARs for this modified SAM of Fig. 3(b) with 4-mm lossy pinna (2-mm shell) at 835 and 1900 MHz, respectively. It should be noted that, by using a modified SAM, an excellent agreement within ±20% (±1 dB) for the peak 10-g SAR is obtained as compared to that obtained for the anatomical models, particularly at the higher frequency of 1900 MHz (see Table II). For the lower frequency




a. 10-g SAR, "Visible Man" Model, cheek position, frequency = 1900 MHz, radiated power = 125 mW.




b. 10-g SAR, Utah Model, 15°-tilted position, frequency = 1900 MHz, radiated power = 125 mW.




c. 1-g SAR, Utah Model, 15°-tilted position, frequency = 835 MHz, radiated power = 600 mW

Fig. 8. Variation of peak 1- or 10-g SAR as a function of separation from the absorptive tissues. Handset of dimensions 22 × 42 × 122 mm.

of 835 MHz, the peak 1- and 10-g SARs given in parentheses in the last column of Table I are still fairly low for the modified

TABLE III
MAXIMUM ALLOWABLE POWERS OF SOME TYPICAL CELLULAR TELEPHONES AT 835 MHz PERMITTED BY THE SAR LIMITS OF IEEE (1999), ICNIRP, AND PROPOSED IEEE (2004) [4]–[6] GUIDELINES. USED FOR CALCULATIONS IS THE UTAH ANATOMIC MODEL WITH 14-mm-THICK EAR

| Config-uration | Handset dimensions (mm) | Antenna axial length (mm) | Maximum Allowable Power in mW | | | |
|---|---|---|---|---|---|---|
| | | | **Present IEEE Standard [4],** 1.6 W/kg for any 1-g of tissue | **ICNIRP Standard [5],** 2.0 W/kg for any 10-g of tissue | **Proposed IEEE Standard [6],** 2.0 W/kg for any 10-g of head tissue; 4.0 W/kg for any 10-g of pinna tissue | **Proposed IEEE Standard [6],** 2.0 W/kg for any 10-g of head tissue; SAR in pinna ignored as for SAM |
| Cheek | 22×42×122 | 80 mm, monopole | 100.2 | 263.7 | 537.9 | 1290.3 |
| | 22×42×122 | 20 mm, helix | 66.2 | 181.5 | 358.8 | 937.5 |
| 15°-tilted | 22×42×122 | 80 mm, monopole | 109.1 | 269.1 | 515.6 | 1153.8 |
| | 22×42×102 | 80 mm, monopole | 129.4 | 341.9 | 688.9 | 1425.2 |
| 15°-tilted | 22×42×122 | 20 mm, helix | 74.1 | 202.0 | 383.0 | 983.6 |
| | 22×42×102 | 20 mm, helix | 87.8 | 242.4 | 467.1 | 1054.5 |
| | 22×42×82 | 20 mm, helix | 127.2 | 320.9 | 596.6 | 1040.8 |

TABLE IV
MAXIMUM ALLOWABLE POWERS OF SOME TYPICAL CELLULAR TELEPHONES AT 1900 MHz PERMITTED BY THE SAR LIMITS OF IEEE (1999), ICNIRP, AND PROPOSED IEEE (2004) [4]–[6] GUIDELINES. USED FOR CALCULATIONS IS THE UTAH ANATOMIC MODEL WITH 14-mm-THICK EAR

| Config-uration | Handset dimensions (mm) | Antenna axial length (mm) | Maximum Allowable Power in mW | | | |
|---|---|---|---|---|---|---|
| | | | **Present IEEE Standard [4],** 1.6 W/kg for any 1-g of tissue | **ICNIRP Standard [5],** 2.0 W/kg for any 10-g of tissue | **Proposed IEEE Standard [6],** 2.0 W/kg for any 10-g of head tissue; 4.0 W/kg for any 10-g of pinna tissue | **Proposed IEEE Standard [6],** 2.0 W/kg for any 10-g of head tissue; SAR in pinna ignored as for SAM |
| Cheek | 22×42×122 | 40 mm, monopole | 86.6 | 240.4 | 427.4 | 892.9 |
| | 22×42×122 | 20 mm, helix | 78.7 | 215.5 | 387.6 | 757.6 |
| 15°-tilted | 22×42×122 | 40 mm, monopole | 66.7 | 188.0 | 337.8 | 925.9 |
| | 22×42×102 | 40 mm, monopole | 71.5 | 198.4 | 352.1 | 925.9 |
| | 22×42×82 | 40 mm, monopole | 70.7 | 196.9 | 347.2 | 961.5 |
| 15°-tilted | 22×42×122 | 20 mm, helix | 58.0 | 164.5 | 299.4 | 862.1 |
| | 22×42×102 | 20 mm, helix | 61.9 | 172.4 | 308.6 | 862.1 |
| | 22×42×82 | 20 mm, helix | 60.2 | 167.8 | 299.4 | 892.9 |

SAM model if the currently used conductivity $\sigma = 0.9$ S/m is assumed for the calculations. However, if a higher conductivity $\sigma = 1.4$ S/m is used for the filler medium, the higher SARs in much better agreement with those for the anatomic models are obtained (see Table I, footnote 2).

## VII. COMPARISON OF MAXIMUM ALLOWABLE POWERS FOR THE SAR LIMITS OF VARIOUS SAFETY GUIDELINES

As mentioned in Section I, the SAR compliance limits are considerably different between the two commonly used RF safety guidelines today. For the IEEE (1999) safety guidelines enforced by the Federal Communications Commission (FCC) in the U.S. [4], the SAR limit is 1.6 W/kg for any 1 g of tissue. The ICNIRP (1998) limit followed in the European Union, Japan, Australia, and many other countries of the world [5] is somewhat higher at 2 W/kg for any 10 g of tissues. While claiming to harmonize with the ICNIRP SAR limits, the IEEE Standards Coordinating Committee 28.4 Draft Standard (2004) [6], if passed, would set a limit of 2 W/kg for any 10 g of tissues applied only to body, i.e., head tissues, while a higher limit of 4 W/kg will be used for the pinna tissues. As a significant amount of power is absorbed for the pinna tissues for cellular telephones held against the ear, this would have a major impact on the maximum allowable powers for cellular telephones.

Using the aforementioned Utah model of the head with a pinna thickness of 14 mm [see Fig. 2(a)], we have calculated the SAR distributions for a variety of handsets using monopole or helix antennas both for cheek and 15°-tilted positions. Tables III and IV give the calculated maximum allowable powers for the various handsets that would result in the peak 1-g or 10-g SARs allowed by the current and proposed IEEE and ICNIRP guidelines at 835 and 1900 MHz, respectively. As expected, the maximum allowable power is 2.5–3 times higher for the higher ICNIRP limit of 2 W/kg for any 10 g of tissue as against the current IEEE (1999) SAR limit of 1.6 W/kg for any 1 g of tissue. Ignoring SAR in the pinna, as for the plastic-ear SAM, and focusing on 2 W/kg only for the head tissues, the proposed IEEE (2004) Standard [6], on the other hand, would allow powers that are up to 5.3 times higher than those of ICNIRP, thus vitiating a desire for harmonized SAR limits throughout the world. Even if the SAR in a lossy pinna, such as for the proposed modified SAM (Section VI), is measured and required to be no more than 4 W/kg for any 10 g of pinna tissues, the proposed IEEE Standard [6] would still allow radiated powers of cellular telephones that may be up to two times higher than those permitted under the ICNIRP SAR limits [5], once again leaving a discord amongst the safety limits used worldwide for SAR compliance of cellular telephones.

## VIII. Conclusions

We have used 3-D CAD files of the SAM model with 1-mm resolution to calculate peak 1- and 10-g SARs for “cheek” and 15°-tilted positions of some typical telephones for comparison with those for three anatomic models of the head. Similar to the results reported earlier, the peak 1- and 10-g SARs for a plastic pinna model such as SAM are up to a factor of two or more times smaller than those obtained for anatomic models primarily due to the physical separation of the radiating antenna from the tissue-simulant absorptive phantom. Visualization of the peak 1- and 10-g SAR regions reveal that, like the previously reported data for plastic-ear SAM-like models [7], [8], use of a plastic spacer for SAM results in shifting the high SAR region to the region of the cheek that corresponds to the area of low radiated fields away from the antenna, particularly at 835 MHz while a similar effect does not occur for anatomic models where the highest SAR region is further up on the handset and always close to the base of the antenna [9], [10]. Another handicap of the plastic-ear SAM model is the total lack of knowledge for 1- or 10-g SAR in the pinna tissues required by all safety guidelines (current or proposed) [4]–[6].

To remedy this situation, we propose a modified SAM with the current plastic spacer replaced by a lossy tissue-simulant fluid with the external shell thickness of only 2 mm as for the rest of SAM. This modified SAM gives 1- and 10-g SARs that are within ±20% of those obtained for anatomic models, provided we use a fluid of higher conductivity than that currently used at 835 MHz.

Lastly, we have compared the implications of the current IEEE and ICNIRP guidelines [4], [5] and the proposed IEEE guideline ([6]—with a relaxed limit of 4.0 W/kg for any 10 g of tissue of the pinna) for maximum allowable powers for cellular telephones at 835 and 1900 MHz. We show that the proposed, relaxed IEEE guideline [6] will allow radiated powers that may be 8–16 times those permitted by the current IEEE standard [4] and up to two times those permitted under ICNIRP guidelines [5]. This vitiates a desire for harmonization with the ICNIRP Standard in this regard.

## References


[1] O. P. Gandhi and G. Kang, “Some present problems and a proposed experimental phantom for SAR compliance testing of cellular telephones at 835 and 1900 MHz,” *Phys. Med. Biol.*, vol. 47, pp. 1501–1518, 2002.

[2] *Basic Standard for Measurement of Specific Absorption Rate Related to Human Exposure to Electromagnetic Fields from Mobile Phones (300 MHz-3 GHz)*, CENELEC Eur. Standard EN50361, 2001.

[3] *Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Body Due to Wireless Communications Devices: Measurement Techniques*, IEEE Standard 1528, 2003.

[4] *IEEE Standard for Safety Levels with Respect to Human Exposure to Radiofrequency Electromagnetic Fields, 3 kHz to 300 GHz*, IEEE Standard C95.1, 1999.

[5] ICNIRP, “Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz),” *Health Phys.*, vol. 74, pp. 494–522, 1998.

[6] *Standard for Safety Levels with Respect to Human Exposure to Radiofrequency Electromagnetic Fields, 3 kHz to 300 GHz, Draft Standard*, IEEE Standards Coordinating Committee 28.4, 2003.

[7] Q. Balzano, O. Garay, and T. J. Manning, Jr., “Electromagnetic energy exposure of simulated users of portable cellular telephones,” *IEEE Trans. Vehicular Technol.*, vol. 44, pp. 390–403, Aug. 1995.

[8] J. P. Oliver, C. K. Chou, and Q. Balzano, “Testing the effectiveness of small radiation shields for mobile phones,” *Bioelectromagnetics*, vol. 24, pp. 66–69, 2003.

[9] M. Okoniewski and M. A. Stuchly, “A study of the handset antenna and human body interaction,” *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 1855–1864, Oct. 1996.

[10] O. P. Gandhi, G. Lazzi, and C. M. Furse, “Electromagnetic absorption in the human head and neck for mobile telephones at 835 and 1900 MHz,” *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 1884–1897, Oct. 1996.

[11] P. J. Dimbylow and S. M. Mann, “SAR calculations in an anatomically-based realistic model of the head for mobile communication transceivers at 900 MHz and 1.8 GHz,” *Phys. Med. Biol.*, vol. 39, pp. 1537–1553, 1994.

[12] A. Taflove, Ed., *Advances in Computational Electrodynamics: The Finite-Difference Time-Domain Method*. Boston, MA: Artech House, 1998.

[13] A. Taflove and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*. Boston, MA: Artech House, 2000.

[14] M. A. Jensen and Y. Rahmat-Samii, “EM interaction in handset antennas and a human in personal communications,” *Proc. IEEE*, vol. 83, pp. 7–17, Jan. 1995.

[15] O. P. Gandhi and J. Y. Chen, “Electromagnetic absorption in the human head from experimental 6 GHz handheld transceivers,” *IEEE Trans. Electromagn. Compat.*, vol. 37, pp. 547–558, Nov. 1995.

[16] A. D. Tinniswood, C. M. Furse, and O. P. Gandhi, “Computations of SAR distributions for two anatomically based models of the human head using CAD files of commercial telephones and the parallelized FDTD code,” *IEEE Trans. Antennas Propagat.*, vol. 46, pp. 829–833, June 1998.

[17] A. D. Tinniswood, G. Lazzi, and O. P. Gandhi, “The use of the expanding-grid FDTD method for simulation of CAD-derived personal wireless telephones,” *Microwave Opt. Technol. Lett.*, vol. 22, pp. 24–29, 1999.

[18] G. Lazzi and O. P. Gandhi, “On modeling and personal dosimetry of cellular telephone helical antennas with the FDTD code,” *IEEE Trans. Antennas Propagat.*, vol. 46, pp. 525–530, Apr. 1998.

[19] *IEEE Recommended Practice for Measurements and Computations of Radiofrequency Electromagnetic Fields with Respect to Human Exposure to Such Fields, 100 kHz–300 GHz*, IEEE Standard C95.3–2002, 2003.

[20] G. Kang and O. P. Gandhi, "SAR's for pocket-mounted mobile telephones at 835 and 1900 MHz," *Phys. Med. Biol.*, vol. 47, pp. 4301–4313, 2002.

**Om P. Gandhi** (S'57–M'58–SM'65–F'79–LF'99) is currently a Professor of electrical engineering at the University of Utah, Salt Lake City. He was Chairman of the Department of Electrical Engineering, University of Utah (1992–1999). He has authored or coauthored several book chapters and over 200 journal papers on EM dosimetry, microwave tubes, and solid-state devices. He also edited *Biological Effects and Medical Applications of Electromagnetic Energy* (Englewood Cliffs, NJ: Prentice-Hall, 1990), and coedited *Electromagnetic Biointeraction* (New York: Plenum, 1989). He is listed in *Who's Who in the World*, *Who's Who in America*, *Who's Who in Engineering*, and *Who's Who in Technology, Today*.

Dr. Gandhi was elected a Fellow of the American Institute for Medical and Biological Engineering in 1997. He was president of the Bioelectromagnetics Society (1992–1993), cochairman of the IEEE SCC 28.IV Subcommittee on RF Safety Standards (1988–1997), and chairman of the IEEE Committee on Man and Radiation (COMAR) (1980–1982). He was the recipient of the d'Arsonval Medal of the Bioelectromagnetics Society for pioneering contributions to the field of bioelectromagnetics in 1995, the Microwave Pioneer Award of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) in 2001, and the State of Utah Governor's Medal for Science and Technology in 2002.

**Gang Kang** (M'01–SM'03) received the B.S and M.S. degrees in electrical engineering from Xidian University, Xi'an, China, in 1988 and 1991, respectively, and the Ph.D. degree in electrical engineering from Peking University, Beijing, China, in 1998.

From 1991 to 1994, he was a Lecturer with Xidian University. From 1997 to 1998, he was a Lecturer with Peking University. From June 1998 to December 1999, he was a Post-Doctoral Research Associate with the Center for Computational Electromagnetics, University of Illinois at Urbana-Champaign. From December 1999 to February 2004, he was a Research Assistant Professor with the Department of Electrical and Computer Engineering, University of Utah, Salt Lake City. He is currently with the Electrical Engineering Department, Duke University, Durham, NC. His research interests include numerical techniques for electromagnetics and their applications in bioelectromagnetics, scattering, antenna design, and EM compatibility.