FDTD Computation of Fat Layer Effects on the SAR Distribution in a Multilayered Superquadric-Ellipsoidal Head-Model Irradiated by a Dipole Antenna at 900/1800 MHz

Liang-Chen Kuo
Department of Electrical Engineering,
National Cheng Kung University
1 University Road, Tainan, Taiwan, R.O.C
Tel: +886 6 2763890 Fax: +886 6 2748690
e-mail:n2887124@sparc1.ncku.edu.tw

Huey-Ru Chuang
Department of Electrical Engineering,
National Cheng Kung University
1 University Road, Tainan, Taiwan, R.O.C
Tel: +886 6 2763890 Fax: +886 6 2748690
e-mail: chuangh@ee.ncku.edu.tw

Abstract: This paper presents FDTD computation of fat layer effects on the SAR distribution in a head model proximate to a dipole antenna at 900/1800MHz. The human head is modeled to be a multi-layered superquadric ellipsoid, which is flexible to model a sphere, ellipsoid, square cube, or rectangular cube. The ellipsoidal head model (with the ears) comprises 9 different tissues (if with a fat layer) of skin, cartilage, fat, muscle, bone, blood, nerve, brain, and eye-lens. A finite radius half-wavelength dipole antenna (corresponding to a length of 16.0/8.0cm at 900/1800MHz) is used for study. Three cases of the fat layer in the head model are considered: (1) without, (2) with a 2.5-mm, and (3) with a 5.0-mm thickness fat layer. It is observed that the head model with a 2.5 or 5.0-mm fat layer has almost the same SARs (for peak-SAR: about 18 mW/g at 900MHz, and 24 mW/g at 1800MHz) However, the head without a fat layer has lower SARs at 900 MHz(for peak-SAR: about 15 mW/g) at but higher SARs at 1800 MHz (for peak-SAR: about 28 mW/g) than those values of the head with a fat layer..

Keywords: Dipole antenna, finite difference time domain (FDTD), fat layer, head mode, multilayered superquadric ellipsoid, SAR distribution.

Theory

Although many research efforts have been devoted to evaluation of EM interaction between the human body (particularly the head) and the handset dipole antennas, the fat layer effects of the human head on the SAR distribution has not particularly been investigated yet. Since the conductivity and permittivity of the fat tissue are much smaller than those of other tissues of the human head, the fat layer will behave like a "shielding" structure. The shielding will cause RF energy not to be able to penetrate into the muscle tissue and may even accumulate in the fat layer of the head and the ear region. In order to quantify conveniently the effect of the fat-layer in the human head on the SAR distribution, here a multilayered superquadric ellipsoidal head model is used. From the concept of the superquadric loop antenna [1,2], which is flexible to model the circular, elliptic, and square loops, the human head is modeled to be a multi-layered superquadric ellipsoid, which is flexible to model a sphere, ellipsoid, square or rectangular cube. The parametric expression of a superquadric ellipsoid modeling is given by

$$\left|(x-x_o)/a_i\right|^{v}+\left|(y-y_o)/b_i\right|^{v}+\left|(z-z_o)/c_i\right|^{v}=1 \qquad (1)$$

where a_i, b_i, c_i are the *i*-th layer axial length, *v* is exponent, and (x_o, y_o, z_o) is the center of superquadric ellipsoid. If *a*=*b*=*c* and *v*=*2*, it is a sphere. If $a \neq b \neq c$ and *v*=*2*, it is an ellipsoid. If *v* is

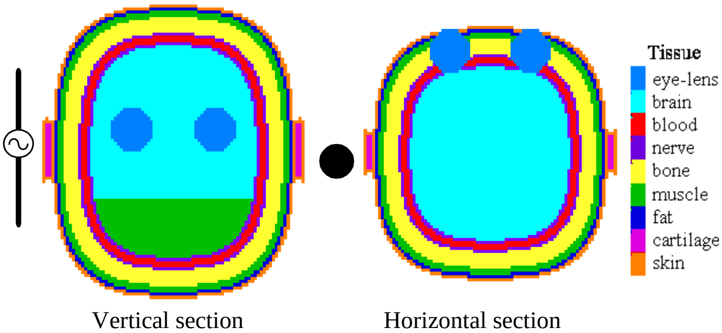

Fig. 1. Multilayered superquadric ellipsoidal model of human head (*a*=*b*=11cm, *c*=12.5cm; *v*=*3*) in the y-z and y-x plane (through eye-layer) with a proximate dipole antenna.

TABLE I
DIELECTRIC PROPERTIES AND TISSUE DENSITIES AT 900/1800 MHZ

Tissue	$\rho\ (g/cm^3)$	900 MHz		1800 MHz	
		ε_r	$\sigma\ (S/m)$	ε_r	$\sigma\ (S/m)$
skin	1.01	43.7	0.86	41.4	1.21
cartilage	1.10	42.7	0.78	40.2	1.29
muscle	1.04	56.0	0.97	54.4	1.39
fat	0.92	11.3	0.11	11.0	0.19
bone	1.81	20.8	0.34	19.3	0.59
nerve	1.01	68.6	2.41	67.2	2.92
blood	1.06	61.4	1.54	59.4	2.04
brain	1.04	45.8	0.77	43.5	1.15
eye-lens	1.05	46.6	0.79	45.4	1.15

large enough, for example *v*=20, it is almost a rectangular cube. It is then easy to define the head-shape and tissue properties. An ellipsoidal head model (*a*=*b*=11cm, *c*=12.5cm; *v*=3) comprises 9 different tissues of skin, cartilage, fat, muscle, bone, blood, nerve, brain, and eye-lens, as shown in Fig. 1 (with a fat layer).

The ear, including skin- and cartilage-layer, is also modeled by using two layers in .the multi-layered superquadric ellipsoid. The skin-layer (of the ear) is modeled by thickness of one FDTD cell

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **19 NOV 2004**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE
FDTD Computation of Fat Layer Effects on the SAR Distribution in a Multilayered Superquadric-Ellipsoidal Head- Model Irradiated by a Dipole Antenna at 900/1800 MHz

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Electrical Engineering, National Cheng Kung University 1 University Road, Tainan, Taiwan, R.O.C

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001732, 2003 IEEE International Symposiun on Electromagnetic Compatibility (EMC) held in Istanbul, Turkey on 11-16 May 2003., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

(the cell size is 2.5 mm which will be discussed later) and the parameters are set to (1.75<a<2.0cm, 10.75<b<11cm, 2.25<c<2.5cm). The cartilage-layer is modeled by thickness of two cells and the parameters are set to (a<1.75cm, 10.25<b<10.75cm, c<2.25cm). Table I shows the dielectric properties and tissue densities at 900/1800 MHz [3]. Note that the tissues of the oral cavity (with the tongue) are assigned to the muscle property. When modeling structures of a finite radius thin-wire dipole is derived with the sub-cell set equations of the contour integral formulation of Maxwell's equations [4]. These FDTD approximations are used to determine the radiation by a center-fed dipole antenna. In the sub-cell approach, a thin wire of finite radius is simulated by assuming that the circumferential magnetic field components and the radial electric field components surrounding the wire vary as 1/r near the wire.

Since the antenna input power P_{in} should be equal to the sum of the head absorbed power P_{abs}, the radiation power P_{rad}, and the ohmic-loss power P_c, these quantities can be used to check the EM coupling computation accuracy. The computation error is defined as [2]

$$\text{computation error} = \left| P_{in} - (P_{rad} + P_{abs} + P_c) \right| / P_{in} \qquad (2)$$

Numerical Results

The head model that is constituted of total 438,118 cubic cells with a cell size of 2.5mm for stability leads to a time step of 4.169ps. A finite radius half-wavelength dipole antenna (corresponding to a length of 16.0/8.0cm at 900/1800MHz) proximate to the head model is partitioned into 63/31 segments (segment size equals to FDTD cell size 2.5mm). A 2nd-order Mur absorbing boundary condition (2nd-Mur ABC) is used for FDTD computation. Transient excitation for 4000/2000 time steps using a Gaussian sinusoidal pulse has ensured the calculated converged results at 900MHz/1800MHz. Note that the computed SAR definitions, the spatial peak-SAR has been computed in a single cubic cell and averaged over 0.015625g (since cell size is 2.5mm). SAR averaged over 1g (SAR_{1g}) is obtained by considering a cubic sample of 64 cells, and total-averaged SAR is obtained by considering the total cubic cells (438,118 cells) of the head. The SAR distribution profiles, antenna radiation power and head-absorbed power will be computed and plotted.

A. Without a Fat Layer

Tables II and III show the computational results of the human head without a fat layer with a dipole antenna at various distances from 1.0 ~ 2.5cm. Note that the antenna input power is kept to be 1W for comparison with the power absorbed by the head and EM radiation power to free space. For example, the distance 1.0cm case, the SAR's (peak, peak-averaged over 1g and total-averaged) are (14.95, 10.57, 0.1) mW/g at 900MHz and (28.88, 20.03, 0.068) mW/g at 1800MHz. For the 1.0cm distance, the spatial SAR distribution profiles are shown in Fig. 2(a) and Fig. 3(a).

B. With a Fat Layer (2.5 mm thickness)

Tables IV and V show the computational results for a 2.5-mm fat layer. Compared with the data listed in Tables II and III (without a fat layer), for 1.0cm distance, the peak-SAR (17.8mW/g) with a fat layer is higher than that (14.95mW/g) without a fat layer at 900MHz. On the contrary, at 1800MHz the peak-SAR (24.9mW/g) with a fat layer is less than that (28.9mW/g) without a fat layer. For 1.0cm distance, the spatial SAR distribution profiles are shown in Fig. 2(b) and Fig. 3(b).

C. With a Fat Layer (5.0 mm thickness)

Tables VI and VII show computational results for a 5.0-mm fat layer. Compared with the data listed in Tables IV and V (with a 2.5-mm fat layer), for 1.0cm distance, it is observed that the peak-SAR (18.54mW/g) with a 5.0-mm fat layer is higher than that (17.83mW/g) with a 2.5-mm fat layer at 900MHz. On the contrary, at 1800MHz the peak-SAR (24.29mW/g) with a 5.0-mm fat layer is less than that (24.92mW/g) with a 2.5-mm fat layer. For the 1.0cm distance, the spatial SAR distribution profiles are shown in Fig.2(c) and Fig.3(c). The following table summaries the comparison.

Table IX. Comparison of SAR values at 900 and 1800 MHz

Dipole-head distance = 1.0 cm	**Peak-/ Peak-averaged (over 1g)/ Total-averaged SAR (mW/g)**	
	900 MHz	**1800 MHz**
No fat layer	14.95/ 10.57/ 0.1	28.88/ 20.03/ 0.068
2.5-mm fat layer	17.83/ 11.24/ 0.103	24.92/ 15.65/ 0.067
5.0-mm fat layer	18.54/ 11.51/ 0.103	24.29/ 15.2/ 0.065

Summary and Conclusion

FDTD computation of fat layer effects on the SAR distribution a head model closed to a dipole antenna at 900 and 1800 MHz is presented. In order to quantify conveniently the effect of the fat-layer in the human head on the SAR distribution, the head is modeled to be a multi-layered superquadric ellipsoid. The ellipsoidal head model (with the ears) comprises 9 different tissues (if with a fat layer) of skin, cartilage, fat, muscle, bone, blood, nerve, brain, and eye-lens. A finite radius half-wavelength dipole antenna (corresponding to a length of 16.0/8.0cm at 900/1800MHz) is proximate to the head model with a distance of 1.0cm.

Three cases of the fat layer in the head model are considered: (1) without, (2) with a 2.5-mm, and (3) with a 5.0-mm thickness fat layer. It is observed that the head model with a 2.5 or 5.0-mm fat layer has almost the same SARs (for peak-SAR: about 18 mW/g at 900MHz, and 24 mW/g at 1800MHz) However, the head without a fat layer has lower SARs at 900 MHz(for peak-SAR: about 15 mW/g) at but higher SARs at 1800 MHz (for peak-SAR: about 28 mW/g) than those values of the head with a fat layer. The study of fat layer effects of the head may be important for the investigation of the exposure assessment for the wireless handset antenna.

References

[1] M. A. Jensen and Y. Rahmat-Samii, "Electromagnetic characteristics of superquadric wire loop antennas," *IEEE Trans. Antennas Propagat.*, vol. 42, pp. 264-269, Feb. 1994.

[2] W. T. Chen and H. R. Chuang, "Numerical Computation of Human Interaction with Arbitrarily-Oriented Superquadric Loop Antennas in Personal Communications," *IEEE Trans. Antennas Propagat*, vol. 46, no. 6, pp. 821-828, June 1998.

[3] M, Burkhardt and N. Kuster, "Appropriate Modeling of the Ear for Compliance Testing of Handheld MTE with SAR Safety Limits at 900/1800MHz," *IEEE Transactions on Microwave Theory and Techniques*, vol. 48, No. 11, pp. 1927-1934, Nov. 2000.

[4] P. A. Tirkas and C. A. Balanis, "Modeling of thin dielectric structures using the finite-difference time-domain technique," *IEEE Trans. Antennas and Propagation.*, vol. 39, pp. 1338-1344, 1991.

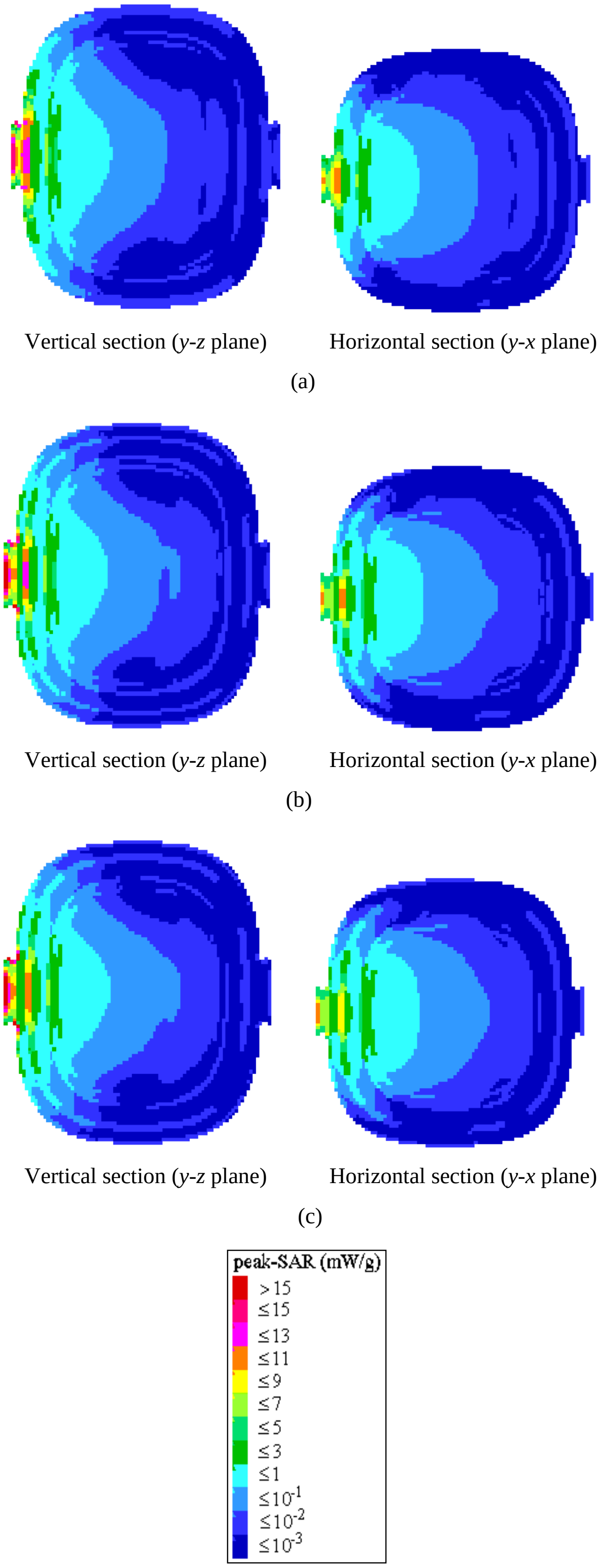

Fig. 2 Spatially peak-SAR profile of the head model in vertical section (*y-z* plane, max-value layer) and horizontal section (*y-x* plane, through eye-layer) proximate to the dipole antenna with 1.0 cm distance at 900 MHz: (a) without a fat layer, (b) with a 2.5mm fat layer, (c) with a 5.0mm fat layer.

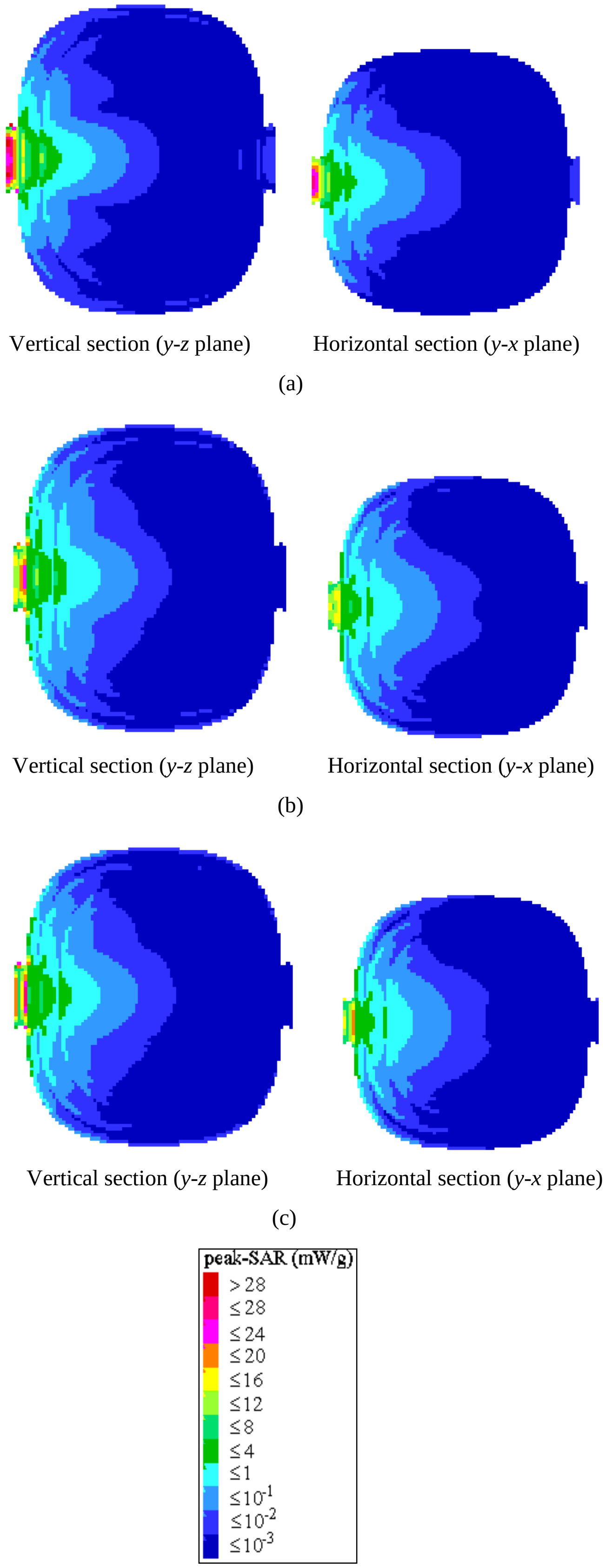

Fig. 3 Spatially peak-SAR profile of the head model in vertical section (*y-z* plane, max-value layer) and horizontal section (*y-x* plane, through eye-layer) proximate to the dipole antenna with 1.0 cm distance at 1800 MHz: (a) without a fat layer, (b) with a 2.5mm fat layer, (c) with a 5.0mm fat layer.

TABLE II Computational results of the human head without a fat layer at 900 MHz

		Without a Fat Layer			
Antenna Position (cm)	In Free Space	2.5	2.0	1.5	1.0
Input Impedance (Ω)	73.76+j6.74	41.66+j26.63	38.76+j19.29	37.47+j11.38	38.26+j2.88
Input Power P_i (W)	1	1	1	1	1
Radiation Power (to free space) P_{rad} (W)	0.999	0.584	0.471	0.389	0.228
Body-Absorbed Power P_b (W)	----	0.449	0.54	0.644	0.761
Ohmic-Loss P_c (W)	0.002	0.003	0.003	0.003	0.003
Peak-SAR (mW/g)	----	4.46	6.37	9.61	14.95
SAR_{1g} (mW/g)	----	3.67	5.2	7.36	10.57
total-averaged SAR (mW/g)	----	0.06	0.072	0.085	0.1
Computation Error (%)	0.05	3.5	1.42	0.54	0.83

TABLE III Computational results of the human head without a fat layer at 1800 MHz

		Without a Fat Layer			
Antenna Position (cm)	In Free Space	2.5	2.0	1.5	1.0
Input Impedance (Ω)	85.39+j22.46	87.49+j38.75	77.29+j39.67	66.37+j35.99	57.08+j27.21
Input Power P_i (W)	1	1	1	1	1
Radiation Power (to free space) P_{rad} (W)	0.994	0.738	0.673	0.567	0.423
Body-Absorbed Power P_b (W)	----	0.237	0.312	0.424	0.604
Ohmic-Loss P_c (W)	0.001	0.001	0.001	0.001	0.001
Peak-SAR (mW/g)	----	7.77	11.27	17.21	28.88
SAR_{1g} (mW/g)	----	5.5	8.05	12.41	20.03
total-averaged SAR (mW/g)	----	0.026	0.034	0.048	0.068
Computation Error (%)	0.47	2.33	1.36	0.76	3.07

TABLE IV Computational results of the human head with a fat layer (2.5 mm thickness) at 900 MHz

		With a Fat Layer (2.5 mm thickness)			
Antenna Position (cm)	In Free Space	2.5	2.0	1.5	1.0
Input Impedance (Ω)	73.76+j6.74	48.69+j29.03	45.7+j23.0	44.84+j16.92	46.01+j9.40
Input Power P_i (W)	1	1	1	1	1
Radiation Power (to free space) P_{rad} (W)	0.999	0.56	0.461	0.349	0.239
Body-Absorbed Power P_b (W)	----	0.467	0.561	0.66	0.771
Ohmic-Loss P_c (W)	0.002	0.002	0.002	0.002	0.002
Peak-SAR (mW/g)	----	5.9	8.372	12.02	17.83
SAR_{1g} (mW/g)	----	4.19	5.81	8.04	11.24
total-averaged SAR (mW/g)	----	0.062	0.075	0.088	0.103
Computation Error (%)	0.05	2.92	2.41	1.17	1.26

TABLE V Computational results of the human head with a fat layer (2.5 mm thickness) at 1800 MHz

		With a Fat Layer (2.5 mm thickness)			
Antenna Position (cm)	In Free Space	2.5	2.0	1.5	1.0
Input Impedance (Ω)	85.39+j22.46	79.55+j43.45	68.21+j43.45	56.25+j39.6	45.21+j31.78
Input Power P_i (W)	1	1	1	1	1
Radiation Power (to free space) P_{rad} (W)	0.994	0.687	0.631	0.538	0.403
Body-Absorbed Power P_b (W)	----	0.282	0.345	0.435	0.58
Ohmic-Loss P_c (W)	0.001	0.002	0.002	0.002	0.002
Peak-SAR (mW/g)	----	6.04	9.65	14.5	24.92
SAR_{1g} (mW/g)	----	3.23	4.96	8.31	15.65
total-averaged SAR (mW/g)	----	0.032	0.039	0.049	0.067

TABLE VI Computational results of the human head with a fat layer (5.0 mm thickness) at 900 MHz

		With a Fat Layer (5.0 mm thickness)			
Antenna Position (cm)	In Free Space	2.5	2.0	1.5	1.0
Input Impedance (Ω)	73.76+j6.74	52.69+j28.83	50.11+j23.38	49.29+j17.19	51.12+j10.55
Input Power P_i (W)	1	1	1	1	1
Radiation Power (to free space) P_{rad} (W)	0.999	0.546	0.452	0.349	0.244
Body-Absorbed Power P_b (W)	----	0.475	0.565	0.665	0.768
Ohmic-Loss P_c (W)	0.002	0.002	0.002	0.002	0.002
Peak-SAR (mW/g)	----	6.56	9.1	12.83	18.54
SAR_{1g} (mW/g)	----	4.62	6.17	8.41	11.51
total-averaged SAR (mW/g)	----	0.064	0.076	0.09	0.103
Computation Error (%)	0.05	2.44	2.07	1.74	1.49

TABLE VII Computational results of the human head with a fat layer (5.0 mm thickness) at 1800 MHz

		With a Fat Layer (5.0 mm thickness)			
Antenna Position (cm)	In Free Space	2.5	2.0	1.5	1.0
Input Impedance (Ω)	85.39+j22.46	79.93+j48.24	67.60+j48.43	55.02+j44.77	43.48+j37.61
Input Power P_i (W)	1	1	1	1	1
Radiation Power (to free space) P_{rad} (W)	0.999	0.713	0.657	0.567	0.431
Body-Absorbed Power P_b (W)	----	0.252	0.314	0.406	0.556
Ohmic-Loss P_c (W)	0.001	0.002	0.002	0.002	0.002
Peak-SAR (mW/g)	----	5.52	9.08	13.82	24.29
SAR_{1g} (mW/g)	----	2.38	4.48	7.96	15.2
total-averaged SAR (mW/g)	----	0.029	0.036	0.047	0.065