# MILLIMETER-RESOLUTION MRI-BASED MODELS OF THE HUMAN BODY FOR ELECTROMAGNETIC DOSIMETRY FROM ELF TO MICROWAVE FREQUENCIES

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## I. INTRODUCTION

As the field of bioelectromagnetics has progressed, there has been a need for increasingly sophisticated models of the human body so that realistic sources of electromagnetic fields may be modeled for the assessment of their safety. Higher-resolution models are needed because nonuniform electromagnetic fields from several of the sources of concern are highly localized, and, at times, at microwave frequencies that do not penetrate the body more than a few tens of millimeters. Some examples of these sources are cellular phones, police radars, hair dryers, electric power drills, etc. Whereas simpler models, such as prolate spheroidal models were quite adequate for determining whole-body-averaged SARs, particularly for far-field, plane-wave irradiation conditions in the early years of bioelectromagnetics, for the last ten to fifteen years the focus has been on near-field, partial-body exposures that are encountered in real life. Since the safety guidelines of a whole-body-averaged SAR of 0.4 W/kg for controlled environments and 0.08 W/kg for uncontrolled environments [1] are hardly ever exceeded in real life, the focus in recent years has been to ascertain that peak local SARs do not exceed 8.0 and 1.6 W/kg for any 1 g of tissue for the controlled and uncontrolled environments, respectively.

We have developed a high-resolution model of the whole human body from the MRI scans of a male volunteer. The model has a resolution of 1.974 x 1.974 mm in the horizontal directions, and 3 mm in the vertical direction. The size of this model is 256 x 128 x 610 voxels. The development of this model is described in detail in Section II.

This model has, to date, been used extensively for studying cellular phones with frequencies 835 and 1900 MHz, and for magnetic fields of electric hair dryers, hair clippers, etc. For these studies, only the head and neck of the model were used, giving a model with 114 x 103 x 85 voxels.

Some preliminary studies of the head and neck exposed to a 3-GHz plane wave were also done using this model, by further subdividing the voxels in the vertical direction to give a 1.974 x 1.974 x 1.5 mm resolution model with 114 x 103 x 170 voxels, suitable for the 3-GHz frequency.

Because of the large number of voxels in the whole-body model, we have not run the entire model with this resolution at this time. We have, however, combined the cells to obtain a 6-mm-resolution model, which has been used for exposure to EM fields characteristic of high-voltage power transmission lines.

## II. DEVELOPMENT OF THE HIGH-RESOLUTION HUMAN MODEL

The high-resolution model of the human body was developed from MRI scans of a male human volunteer. A complete set of axial images was acquired, with the imaged volume extending from the top of the head to the sole of the foot. Each image has a slice thickness of 3 mm, and a matrix of 256 x 256 pixels with a 48-cm field-of-view, giving a horizontal pixel size of 1.875 mm. The pulse sequence used in the acquisition is spin echo, with repetition (TR) 600 ms, and echo time (TE) 23 ms. The short TR was chosen to enhance $T_1$ relaxation time differences among soft tissues. Of the three main parameters determining tissue contrast in MR ($T_1$, $T_2$, and spin density), $T_1$ differences produce the highest contrast among soft tissues. For MRI at 1.5 Tesla, the $T_1$ relaxation time of fat is 259 ms, and for muscle it is 869 ms, giving a difference of over 300%. Saturation pulses were added outside the imaging slice to reduce pulsatile blood flow artifacts.

The images were acquired in an interleaved, multislice format to reduce the acquisition time. For example, after acquiring a signal from slice 1, there is a wait of 600 ms before another signal can be acquired from that slice. During that time, signals are acquired from several other slices so that no time is wasted. Even with multislice imaging, the total acquisition time for the images was over 6 hours. Without multislice imaging, the acquisition time would have been about 24 hours.

Since MR scans provide only a plot of tissue density, which does not have a one-to-one correspondence with tissue type, it was necessary to manually define the type of tissue in each region of the MRI scans. This was done with the help of ANALYZE, a software package from the Mayo Clinic. This package allows the user to define regions based on ranges of density, and convert each region into a tissue type. Proceeding to subsequent layers, the density range is repeated, so that large, well-defined organs or bones can be readily defined. This somewhat automated the process of converting from density to tissue type, but it was still a tedious process, requiring a trained anatomist.

The MRI scans were converted into a voxel map of 30 tissue types. These are: muscle, fat, regular bone, compact bone, cartilage, skin, nerve, intestine, spleen, pancreas, heart, blood, parotid gland, liver, kidney, lung, bladder, cerebrospinal fluid, eye humour, eye sclera, eye lens, stomach, erectile tissue, prostate gland, spermatic cord, testicle, ligament, pineal gland, pituitary gland, and brain.

The MRI scans were taken at a resolution of 1.875 mm in the horizontal directions and 3 mm in the vertical direction, giving a model with a total of 256 x 128 x 610 voxels. The height of the volunteer was 176.4 cm, which was quite close to the height of 176 cm for the average "reference" man [2]. The weight of the volunteer was 64 kg, which was somewhat lower than the average weight of 71 kg [2]. To adjust the weight of the model, the voxel size was assumed to be 1.974 mm in the horizontal directions, instead of the original 1.875-mm resolution of the scans. This resulted in a theoretical model weight of 70.93 kg, which is sufficiently close to the average weight of 71 kg.

Several regions of the model required individual attention. Fat and skin were perturbed because of the shift of fat relative to muscle and other water-based tissues. Since position is encoded by frequency in MR imaging, fat will appear to shift in the direction of the read gradient with respect to its true position. The amount of this shift is given by

$$\Delta x = \Delta f / \gamma G \tag{1}$$

where $\Delta x$ is the shift in spatial position, $\Delta f$ is the difference in resonant frequency, $\gamma$ is the gyromagnetic ratio for protons, and G is the amplitude of the read gradient. There is no shift in the phase encoding direction because the phase difference between fat and water from one phase encoding point to the next is constant and does not accumulate.

In the images we acquired, the fat shift was approximately 2 pixels. This is most easily seen in the images of the leg, where the rim of fat is shifted slightly with respect to the muscle it surrounds. This shift of fat was ignored in the MRI-to-tissue encoding, because the fat regions were generally sufficiently large that this 2-pixel shift was not significant.

In future MRI scans, there are two ways to reduce the fat shift. One is to acquire the images at a lower static field strength. Since the frequency difference between fat and muscle depends on the resonant frequency, lowering the static field will reduce the shift. A second way to reduce the fat shift is to increase the amplitude of the readout gradient, and sample the spin echo faster. Unfortunately, both of these approaches reduce the signal-to-noise ratio. If the shift were reduced to less than one pixel in the images, it would probably not be noticeable.

While the fat shift did not cause too much difficulty in defining the regions of fat, it did cause difficulty in defining the skin region. On the read side of the model, the fat shift obliterated the skin layer, making it appear very thin, while on the other side, it appeared very thick. The skin was therefore not defined from the original MRI scans. Instead, a one-voxel-thick layer of skin was added to all exterior regions except the eyes and ear canals using a computer algorithm that searched for exterior surfaces and placed a layer of skin next to them.

Another small problem was that the scans had started too near the top of the head, cutting off about 6 mm of the top of the head. Since this region is simple and well-defined, a computer algorithm was used to add the top layers of bone, fat, and skin.

Another difficulty of the modeling was that the volunteer was in a relaxed position for the MRI scanning process. Using a pillow under his head resulted in the head of the model being slightly forward of a normal standing position. So far this does not appear to have caused difficulty with any of our applications. Leaving the feet in a relaxed position also resulted in tilts of the feet relative to the normal standing position. This did cause difficulty in properly grounding the model for plane-wave exposure simulations. This problem was overcome with a computer algorithm which shifted the ball of the foot upwards, to flatten the foot into a normal standing position. A third problem with the relaxed volunteer was that the arms were not held sufficiently close to the body, and the elbows and outer portions of the forearm are not included in the scan region. This problem has not yet been of significance in our simulations, but will be addressed as needed by manually recreating these regions of the arms.

Another modeling difficulty was caused by not time-gating the MRI scans to eliminate the beating action of the heart. This resulted in a blurry heart image which caused the ANALYZE program to proceed in a jagged fashion through the heart. These jagged regions were removed by hand to smoothen the heart surface. In future MRI scans, the scan acquisition could be synchronized with the heartbeat to give a less blurry image of the heart. The data then could not be acquired in a multislice format for this region, increasing the total acquisition time by about 1/2 hour.

In addition to these overall corrections, careful individual analysis was made of each layer of the model to find and clean up any mistakes made during the MRI to tissue-type conversion. In particular, many slices had spurious data around the outside of the scan region (a square box well outside of the model), because of the particular method of using ANALYZE to convert from MRI to tissue map. Also, the model was acquired in a set of 12 sections, on two different days, and the volunteer was allowed to get out of the MRI machine between some of these sections. Although every attempt was made to place the volunteer in exactly the same location each time, a slight variation was expected, and each section had to be lined up within 3-4 mm by hand.

The theoretical weights of each of the major tissues were calculated based on specific gravities given in [2] and the number of voxels of each tissue in the model. These weights are shown in Table 1 and are compared to the weights of the tissues of the average man given in [2]. Most of the comparisons are excellent. The reasons for some of the discrepancies between theoretical and model weights are given in the footnotes. With resolution under 3 mm, this model has highly recognizable physical attributes.

## III. APPLICATIONS OF THE MAN MODEL

This 1.974 × 1.974 × 3 mm man model has been used in finite-difference time-domain (FDTD) and impedance method simulations for a number of applications ranging from 60 Hz to 3 GHz. The FDTD method is described in [3]. In addition to the 256 × 128 × 610 voxels required by the man model, a minimum of 10 voxels are required between the model and an external artificial absorbing boundary condition used to truncate the simulation region. This gives a total of about 25.7 million voxels required for the FDTD simulation (about 20 million of which are in the man model). When programmed as efficiently as possible, the FDTD method requires 6 real values to be stored for each voxel, and 1 additional value to be stored for the voxels within the man model, so simulation of the whole-body model would require about 700 Mbytes of memory on a machine with 4 bytes per real value.

Since this large memory is beyond the limits of our readily available computer resources, and because we have not had an application requiring both the ultra-high resolution and the whole-body model, we have limited our simulations with this model to either partial-body models (such as the head and neck for cellular phones, small electrical appliances, or for microwave exposures) or to combining the voxels to obtain slightly coarser models (such as a 6-mm-resolution model) for simulation of power-line exposure. For these simulations, memory requirements are below 256 Mbytes so they can be run on many workstations and most mainframe computers.

### Dosimetry for Cellular Telephones at 835 and 1900 MHz

We have used the model of the head and neck to obtain SAR distributions for a number of commercially available cellular telephones operating at transmission frequencies of 820-850 MHz (center frequency of 835 MHz) and the personal communication systems presently under development to operate at the center frequency of 1900 MHz [4]. Of particular interest is a comparison between two lengths of antenna $\lambda/4$ and 3 $\lambda/8$ that were assumed to be mounted on a plastic-covered handset of box size 15 × 6 × 2.5 cm. The salient features of the calculated results are given in Table 2. It is interesting to note that the powers absorbed and the peak SARs are lower for 3 $\lambda/8$ antennas as compared to $\lambda/4$ antennas for 835 MHz but not necessarily for 1900 MHz. This is likely due to the fact that the peak current region for 3 $\lambda/8$ antennas is further up on the antenna and is therefore more distant from the head than for the $\lambda/4$ antenna where it is at the base of the antenna and, hence, very close to the ear. This is particularly true for the physically longer antennas at 835 MHz than at 1900 MHz where both the 3 $\lambda/8$ and $\lambda/4$ antennas are fairly short, of lengths 5.92 and 3.95 cm, respectively. Similar distance-related arguments can also be given for 33°-tilted antennas vis à vis vertically held antennas (tilt angle of 0°) both for 835 and 1900 MHz.

We have also recently used scaled models of the head and neck region to obtain sizes that are characteristic of 10- and 5-year-old children, respectively. Even though the peak 1-g SARs are roughly comparable for each of the models, a deeper penetration of the absorbed energy and higher interior SARs are observed for the smaller models as compared to the model of the adult. Additional work is needed to understand this effect.

### Electric Field and Current Density Distributions Induced in the Human Head and Neck by the Magnetic Fields of a Hair Dryer and a Hair Clipper

We have previously reported on the induced electric field and current density distributions for a 1.31-cm-resolution anatomically based model of the human for magnetic fields of a hair dryer [5]. To pinpoint the magnitudes and the regions of the induced peak electric fields and current densities, we have used the new MRI-based model of the head and neck with a resolution of 1.974 × 1.974 × 3 mm to calculate the induced parameters for the spatially varying magnetic fields of a hair dryer and a hair clipper. The measured magnetic field variations for both of these electrical appliances are used to postulate equivalent magnetic dipoles for which the orientations and the magnitudes are varied to obtain the best fit to the experimental data. We have used the impedance method [6] to calculate the induced electric fields and current densities for the various regions of the model. Because of the high degree of anisotropy in the electrical properties of the skeletal muscle, conductivities of 0.86 and 0.068 S/m have been taken for this tissue for vertical and horizontal directions, respectively. Layer-averaged current densities of 1.1-4.0 $\mu A/m^2$ (a local peak value as high as 79.7 $\mu A/m^2$) and 4.3-17.1 $\mu A/m^2$ (a local peak value as high as 411.5 $\mu A/m^2$) are obtained for the hair dryer and hair clipper, respectively. Appliances selected for these calculations had measured peak magnetic fields of 120 and 390 $\mu T$, respectively, for the region occupied by the model of the head.

### Electric Field and Current Density Distributions in the Model of the Whole Body for EMFS of Power Lines

The FDTD method has previously been used to calculate induced current densities in a 1.31-cm-resolution anatomically based model of the human body for electric and magnetic fields (EMFs) that are typical of high-voltage (HV) power transmission lines at 60 Hz [7]. We have recently completed dosimetric calculations for EMFs of HV power transmission lines using a somewhat coarser version of the new MRI-based model [8]. Since it is not possible to run the whole-body model with a resolution of 1.974 × 1.974 × 3 mm with the memories of computers that are easily available to us, we have combined 3 × 3 × 2 cells along the three axes of the model to get a new model with resolution of 5.922 × 5.922 × 6 mm. The conductivities of the coarser cells were obtained by directional averaging of the conductivities of the finer cells, thereby allowing the anisotropic properties for some of the tissues such as skeletal muscle, etc. The calculated variation of current along the height of the body is in excellent agreement with the experimental data of Deno [9]. The calculated maximum current densities for several layers of the model for the torso and the head regions are higher than 4 and 10 $mA/m^2$ suggested as the upper limits of exposure in the safety guidelines proposed by IRPA and by an international working group of the European communities [10, 11].

## IV. CONCLUSIONS

The development and use of a 1.974 × 1.974 × 3 mm resolution model of the human body has been described. This model was created by converting the MRI-density scans into tissue voxel maps. The model contains 256 × 128 × 610 voxels, and is broken down into 30 tissue types. The theoretical weights of the total model and each individual tissue were compared, and good accuracy is observed.

This model has been used for a number of FDTD and impedance method simulations from microwave to power-line frequencies. The model of the head and neck (114 × 103 × 85 voxels) was used to analyze the interaction of numerous cellular phones at 835 and 1900 MHz with the human head. The electromagnetic interaction with the 60-Hz magnetic fields from an electric hair dryer and a hair clipper were also studied using this model. The original 1.974 × 1.974 × 3 mm model was subdivided into a 1.974 × 1.974 × 1.5 mm model to analyze plane-wave irradiation of the head at 3.0 and 6.0 GHz. In addition, the voxels in the original model were combined to give a 6-mm resolution model of the whole human body, and this new model was used to study the coupling of the power-line EMFs to the human body.

## REFERENCES


1. ANSI/IEEE C95.1-1992, "American National Standard -- Safety Levels with Respect to Human Exposure to Radio-Frequency Electromagnetic Fields, 3 kHz to 300 GHz," published by the Institute of Electrical and Electronics Engineers, Inc., 345 East 47th Street, New York, New York, 10017.

2. "Report of the Task Group on Reference Man," ICRP Publication #23, Pergamon Press, 1992.

3. K. S. Kunz and R. J. Luebbers, *The Finite-Difference Time-Domain Method for Electromagnetics*, CRC Press, Boca Raton, Florida, 1993.

4. O. P. Gandhi, J. Y. Chen, and D. Wu, "Electromagnetic Absorption in the Human Head for Mobile Telephones at 835 and 1900 MHz," *Proceedings of the International Symposium on Electromagnetic Compatibility (EMC '94 Roma)*, September 13-16, 1994, Rome, Italy, pp. 1-5.

5. S. Tofani, P. Ossola, G. d'Amore, and O. P. Gandhi, "Electric Fields and Current Density Distributions Induced in an Anatomically Based Model of the Human Head by Magnetic Fields from a Hair Dryer," *Health Physics*, Vol. 68, pp. 71-79, 1995.

6. O. P. Gandhi, "Numerical Methods for Specific Absorption Rate Calculations," Chapter 6, *Biological Effects and Medical Applications of Electromagnetic Energy*, O. P. Gandhi, editor, Prentice-Hall, Inc., New York, pp. 113-140, 1990.

7. O. P. Gandhi and J. Y. Chen, "Numerical Dosimetry at Power-Line Frequencies Using Anatomically Based Models," *Bioelectromagnetics Supplement 1*, pp. 43-60, 1992.

8. C. M. Furse, J. Y. Chen, and O. P. Gandhi, "Calculation of Electric Fields and Currents Induced in a Millimeter-Resolution Human Model at 60 Hz Using the FDTD Method with a Novel Time-to-Frequency-Domain Conversion," to appear in *Bioelectromagnetics.*

9. D. W. Deno, "Currents Induced in the Human Body by High-Voltage Transmission-Line Electric Field -- Measurement and Calculation of Distribution and Dose," *IEEE Transactions on Power Apparatus and Systems*, Vol.. 96, pp. 1517-1527, 1977.

10. IRPA, "Interim Guidelines on Limits of Exposure to 50/60-Hz Electric and Magnetic Fields," *Health Physics*, Vol. 58, pp. 113-122, 1990.

11. S. G. Allen et al., "Proposals for Basic Restrictions for Protection Against Occupational Exposure to Electromagnetic Nonionizing Radiations. Recommendations of an international working group set up under the auspices of the Commission of the European Communities," *Physica Medica*, Vol. VII, pp. 77-89, 1991.

Table 1. Comparison of weights of tissues/organs in the MRI-based model with "reference man" [2].

| Tissue Type | Mass Density g/cm$^3$ | No. of Voxels | Weight in grams Model | Weight in grams reference man [2] |
|---|---|---|---|---|
| muscle | 1.047 | 2,604,370 | 31,871 | 28,000 |
| fat | 0.916 | 1,388,947 | 14,873 | 13,500 |
| bone[1] | 1.465 | 564,906 | 9,675 | 10,000 |
| cartilage | 1.097 | 13,839 | 177[2] | 2,500 |
| skin[3] | 0.983 | 289,720 | 3,329 | 2,600 |
| nerve | 1.038 | 5,410 | 65.6[4] | 30[5] |
| intestine | 1.042 | 104,204 | 1,270[9] | 1,010[10] |
| pancreas | 1.045 | 9,394 | 114.8 | 100 |
| heart | 1.030 | 59,236 | 713.1[9] | 450[10] |
| blood | 1.058 | 58,074 | 718[6] | 5,500 |
| liver | 1.030[8] | 146,074 | 1,759 | 1,800 |
| kidney[7] | 1.050 | 24,780 | 304 | 310 |
| lung[7] | 0.347 | 242,731 | 983.8 | 1,000 |
| bladder | 1.030 | 18,053 | 217.4[9] | 150-250 |
| stomach | 1.05 | 47,914 | 588[9] | 150[10] |
| prostate gland | 1.045 | 2,830 | 34.5 | 16 |
| testicle[7] | 1.044 | 7,223 | 88.1 | 60 |
| ligament | 1.22 | 29,472 | 420 | 1,500 |
| pineal gland | 1.048 | 18 | 0.2 | 0.18 |
| pituitary gland | 1.066 | 22 | 0.3 | 0.6 |
| brain | 1.035 | 138,188 | 1,673 | 1,400 |

1 Compact and regular bone combined.

2 Major cartilage regions (ear, nose) only. No bone-end cartilage.

3 1-voxel thick layer around entire body except eyes and ear canal.

4 Spinal cord, optic nerve, other large nerves included.

5 Spinal cord only.

6 Major arteries and vessels only.

7 Pair.

8 No value given. Estimate based on tissue content.

9 Full (contents are not differentiated from organ).

10 Empty (organ only).

Table 2. Powers absorbed and peak SARs for $\lambda/4$ and 3 $\lambda/8$ antennas at 835 and 1900 MHz. Assumed dimensions of the handset are $2.5 \times 6 \times 15$ cm.

| Antenna length | Tilt | Head Peak 1-cm$^3$ SAR W/kg | Brain Peak 1-cm$^3$ SAR W/kg | % power absorbed by "hand" | % power absorbed by head and neck |
|---|---|---|---|---|---|
| **835 MHz; Time-averaged radiated power = 0.6 W** | | | | | |
| $\lambda/4$ | 0° | 1.53 (596 mg)* | 0.97 (877 mg)* | 17.0 | 63.1 |
| $\lambda/4$ | 33° | 1.21 (549 mg)* | 0.54 (713 mg)* | 15.0 | 50.8 |
| 3 $\lambda/8$ | 0° | 0.67 (526 mg)* | 0.35 (877 mg)* | 16.5 | 42.5 |
| 3 $\lambda/8$ | 33° | 0.74 (795 mg)* | 0.68 (877 mg)* | 12.5 | 34.4 |
| **1900 MHz; Time-averaged radiated power = 0.125 W** | | | | | |
| $\lambda/4$ | 0° | 0.86 (503 mg)* | 0.28 (818 mg)* | 22.5 | 46.9 |
| $\lambda/4$ | 33° | 0.86 (503 mg)* | 0.49 (818 mg)* | 22.1 | 45.1 |
| 3 $\lambda/8$ | 0° | 0.71 (503 mg)* | 0.24 (853 mg)* | 17.7 | 48.8 |
| 3 $\lambda/8$ | 33° | 0.85 (561 mg)* | 0.38 (878 mg)* | 17.1 | 46.3 |

* Assumed weight for 1 cm$^3$ of volume.