Parametric Dependence of SAR on Permittivity Values in a Man Model

Peter Gajšek, William D. Hurt, *Senior Member, IEEE,* John M. Ziriax, and Patrick A. Mason*

***Abstract*—The development and widespread use of advanced three-dimensional digital anatomical models to calculate specific absorption rate (SAR) values in biological material has resulted in the need to understand how model parameters (e.g., permittivity value) affect the predicted whole-body and localized SAR values. The application of the man dosimetry model requires that permittivity values (dielectric value and conductivity) be allocated to the various tissues at all the frequencies to which the model will be exposed.**

In the 3-mm-resolution man model, the permittivity values for all 39 tissue-types were altered simultaneously for each orientation and applied frequency. In addition, permittivity values for muscle, fat, skin, and bone marrow were manipulated independently. The finite-difference time-domain code was used to predict localized and whole-body normalized SAR values. The model was processed in the far-field conditions at the resonant frequency (70 MHz) and above (200, 400, 918, and 2060 MHz) for E orientation. In addition, other orientations (K, H) of the model to the incident fields were used where no substantial resonant frequency exists. Variability in permittivity values did not substantially influence whole-body SAR values, while localized SAR values for individual tissues were substantially affected by these changes. Changes in permittivity had greatest effect on localized SAR values when they were low compare to the whole-body SAR value or when errors involved tissues that represent a substantial proportion of the body mass (i.e., muscle).

Furthermore, we establish the partial derivative of whole-body and localized SAR values with respect to the dielectric value and conductivity for muscle independently. It was shown that uncertainties in dielectric value or conductivity do not substantially influence normalized whole-body SAR. Detailed investigation on localized SAR ratios showed that conductivity presents a more substantial factor in absorption of energy in tissues than dielectric value for almost all applied exposure conditions.

***Index Terms*—Dielectric values, dosimetry, electromagnetic fields (EMFs), finite-difference time-domain (FDTD), radio frequency.**

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I. Introduction

THE LAST decade has witnessed significant progress in dosimetry for human exposure to radio-frequency (RF) fields. In recent years, with availability of high-resolution anatomical models of the human body, numerical computations of electric field strength and specific absorption rate (SAR) have been made in several laboratories. Despite limited interlaboratory comparison of the data and their verification, questions remain regarding the reliability of these data because of different methods, design, and model parameters including permittivity.

Currently, there are over 40 tissue types for which permittivity values are available. However, various authors [1]–[13] report different permittivity values for the same tissue types. This lack of consensus on what are the best permittivity values should be used poses the question of the effect of permittivity value on calculated SAR values in biological systems. In this paper, we establish the partial derivative of whole-body and localized SAR (defined as SAR for individual organs) values for the digital anatomical man model (voxel size 3 mm) with respect to a change in the permittivity values of all tissue types, including those tissues with the most variable reported permittivity values by Gabriel [1]. Hurt *et al.* [14]. showed that whole-body SAR is not very sensitive to variations in the published permittivity values, whereas localized SAR show substantial dependence on these values.

Since there is some variability in the tissue permittivity values of human and animals and some uncertainty in the measurement of the permittivity of tissues, the dependence of SAR on permittivity changes is important. Permittivity values (relative dielectric value [ε'] and effective conductivity [σ]) have a dominant role in the overall consideration of interaction between electromagnetic fields (EMFs) and matter and in related applications including electromagnetic dosimetry. Determining permittivity values of various biological tissues is the first step when calculating the SAR. These characteristics are described in many publications [1]–[5], but there are some concerns related to the accuracy of published data. Variability in reported permittivity values for a single organ may result from one or more of the following: different donor species, the heterogeneous nature of the biological tissues, the doner's chronological age, the freshness of the sample, temperature, the tissue preparation procedure, and whether the tissue is anisotropic. In addition, there are reports on systematic errors associated with the measurement technique [1].

The most recent and comprehensive permittivity data have been measured by Gabriel [1], [2] on more than 20 tissue types for the frequency range of 10 Hz to 20 GHz and on more than

ten other types from 10 MHz to 20 GHz. Recently, Hurt *et al.* [14] reported on the permittivity values of biological tissues published elsewhere in literature that deviate substantially from the data published by Gabriel. The ratios that reflect the differences among published data were calculated. Ratios smaller than 0.5 or greater than 2.0 are reported for over 50% of available tissue types. Some tissue types are considered as extreme outliers (ratio either <0.1 or >10). These outliers are generally a consequence of the great inhomogeneity of these tissue types and the difficulty associated with sample preparation for the measurements. Since permittivity is frequency dependent, the ratios vary greatly over the frequency range and generally increase with decreasing frequency.

There is, as yet, no consensus as to which available tissue permittivity values should be used as a reference. To advance RF dosimetry, it is critical to understand how SAR (whole-body and localized) depends on the permittivity values of the various biological tissues in a man model. Localized SAR generally refers to average SAR value of an individual organ or tissue type used in the digital anatomical model of the man. For the purposes of this paper, localized SAR will refer to mean SAR value of individual organs. The primary goal of this study is to determine the sensitivity of SAR to the uncertainty in published permittivity values for particular biological tissues. The partial derivative of SARs (whole-body, localized) with respect to changing the permittivity values of all tissue types, including the permittivity values of those tissues with the most heterogeneous values as reported in the literature [3]–[10], are discussed.

TABLE I
TISSUE TYPES, IN, THEIR NUMBER OF VOXELS, AND ORGAN MASS IN THE MAN MODEL (VOXEL SIZE 3 mm CUBED). NUMBER IN THE FIRST COLUMN CORRESPONDS TO NUMBER ALONG ABSCISSA AXIS IN FIGS. 2–4

IN	Organ	Number of voxels	AFRL Brooks Man model Organ mass (kg)	Reference Man ICRP 23 [22] Organ mass (kg)
1	BILE	711	0.0194	0.0620
2	BODY FLUID	13575	0.3700	?
3	EYE (cornea)	12	0.0003	0.0003
4	FAT	1245612	30.8000	13.5000
5	LYMPH	2677	0.0752	0.0700
6	MUSCOUS MEMBRAN	17621	0.4950	?
7	NAILS (toe & finge)	128	0.0036	0.0030
8	NERVE (spine)	11764	0.3300	0.3000
9	MUSCLE	1588186	44.9000	28.0000
10	HEART	11520	0.3150	0.3300
11	WHITE MATTER	16348	0.4580	0.5000
12	STOMACH	5661	0.1600	0.1500
13	GLANDS	5705	0.1620	0.1650
14	BLOOD VESSEL	20845	0.5850	0.2100
15	LIVER	66244	1.8400	1.8000
16	GALL BLADDER	384	0.0107	0.0100
17	SPLEEN	8988	0.2560	0.1800
18	CEREBELLUM	4321	0.1210	0.1500
19	BONE (cortical)	92457	4.9700	5.0000
20	CARTILAGE	18679	0.5530	1.1000
21	LIGAMENTS	93005	3.0600	1.5000
22	SKIN/DERMIS	167810	5.1000	2.6000
23	INTESTINE (large)	17155	0.4830	0.3720
24	TOOTH	489	0.0285	0.0400
25	GRAY MATTER	20628	0.5780	0.6000
26	EYE (lens)	22	0.0006	0.0005
27	LUNG (outer)	25849	0.7330	0.5000
28	INTESTINE (small)	28592	0.8050	0.6400
29	EYE (sclera/wall)	120	0.0033	0.0030
30	LUNG (inner)	99832	0.7010	0.5200
31	PANCREAS	3116	0.0879	0.1000
32	BLOOD	24094	0.6880	5.2000
33	CEREBRAL SPINAL FL	6750	0.1840	0.1200
34	EYE (vitreous humor)	433	0.0118	0.0100
35	KIDNEYS	12442	0.3530	0.3100
36	BONE MARROW	103047	2.8900	3.0000
37	BLADDER	3812	0.1060	0.0500
38	TESTICLES	783	0.0221	0.0300
39	BONE (cancellous)	60116	3.1200	2.0000
40	**WHOLE BODY**	3799333	105.3759	70.0000

II. METHODS

The normalized localized and whole-body SAR values (W/kg/mW/cm^2) were predicted using a finite-difference time-domain (FDTD) program based on code originally described by Kunz and Luebbers [15]. The FDTD numerical approach is used because it involves discrete, time-domain computations of differential equations applicable for all size objects within the limits of the speed and memory of available computers. In order to bound the domain under study, the scattered field region has been closed by applying a second-order absorbing boundary conditions [15].

The human model used was based on the photographic data from the Visible Human Project created by the National Library of Medicine and the University of Colorado Health Sciences Center. A computer-segmented data set based on the photographic images was created by a collaboration between National University of Singapore and Johns Hopkins University. Each of the 1878 slices in the Z plane was then coded by hand using Adobe Photoshop and a palette of colors that represented 39 tissue types (see Table I). The number of tissue types is based on their size in the body and availability of permittivity properties. Detailed descriptions of the procedures used to construct the digital anatomical database of the man have been presented in Mason *et al.* [16]. The initial anatomical data sets contained 374 million voxels ($1878 \times 340 \times 586$) with each voxel being a cube 1 mm on a side. Calculating EMF exposures with this model requires approximately 18 GB of computer memory for FDTD. Because of the limited power of available computers, we used a smaller version of this data set with a resolution of 3 mm^3. A 3-mm anatomical model was created from the 1-mm model by adding layers of air to one or more sides of the model volume to make the size of the model an even multiple of 3 mm. The reduction then took a cube of $3 \times 3 \times 3$ 1-mm voxels and based on the most common tissue type in that cube creates the single 3-mm voxel. This process was repeated for each $3 \times 3 \times 3$ set of 1-mm voxels. While this greatly reduces the requirement for memory, it also introduced error due to increase voxel size. In addition, very small organs may be distorted or lost, some symmetries may be affected, organs change mass slightly, and the continuity of elongated structures may be disrupted.

To determine the dependence of SAR on the permittivity values, a man model was processed for three different permittivity conditions (lowest, original, highest). We took into account the maximal ratios between original permittivity values published by Gabriel [1] and values (the highest or lowest compare to data published by Gabriel) reported by other authors for a particular tissue [3]–[10]. Ratios in permittivity values for muscle, fat, skin, and bone marrow were taken as worst-case condition for selected frequency. Reported data are not available for all applied frequencies. Thus, a linear extrapolation of permittivity values for all missing frequencies was made. Ratios for permittivity values for individual tissue type according to applied frequency are reported in Table II.

To examine the influence of the frequency on predicted SAR values, the frequency was varied over a relatively wide range including the expected resonance frequency according to data in the RF Dosimetry Handbook that are based on human models

TABLE II
THE HIGHEST AND LOWEST RATIOS (TAKEN AS WORST CASE CONDITION) BETWEEN PERMITTIVITY (RATIOS FOR DIELECTRIC VALUE AND CONDUCTIVITY ARE CHOSEN TO BE IDENTICAL) MEASURED BY GABRIEL [1] AND OTHER AUTHORS [3]–[10] FOR DIFFERENT TISSUE TYPES

Frequency (MHz)	ratio	Muscle	Fat	Skin	Bone Marrow
70	Highest	2.0	7.1	4.0	13.0
	Lowest	0.5	0.5	0.5	1.0
200	Highest	2.0	5.0	4.6	10.0
	Lowest	0.5	0.5	0.5	1.0
400	Highest	2.0	3.5	4.4	9.0
	Lowest	0.5	0.5	0.5	1.0
918	Highest	2.0	1.8	4.7	7.0
	Lowest	0.5	0.5	0.5	1.0
2060	Highest	2.0	2.5	4.0	4.0
	Lowest	0.5	0.5	0.5	1.0

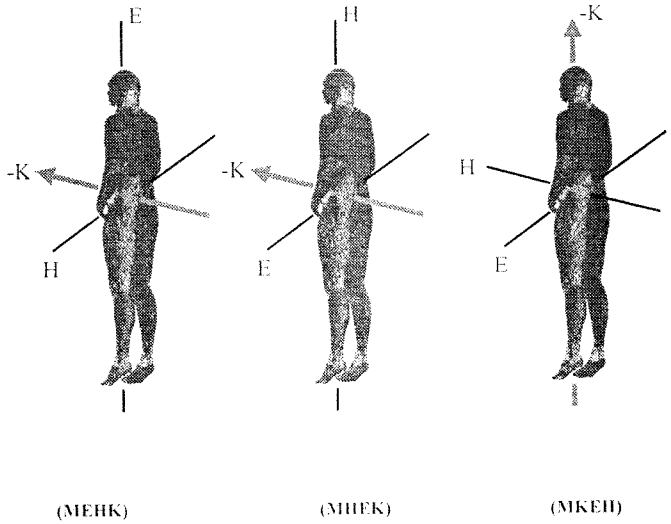


Fig. 1. Representations of the four orientations examined (MEHK, MHEK, MKHE). The following three vectors comprise EMFs: the electric field (E-measured in V/m), magnetic field (H-measured in A/m), and direction of propagation (K). Orientation of the object with regard to the direction of propagation was dorsal (M).

constructed from prolate spheroids and ellipsoids [17]. The voxel size, generally limited to one-eighth of the wavelength by this version of the FDTD code, represents the main limitations on the highest frequencies examined in our study. At the highest frequency examined, 2060 MHz, the wavelength inside the body was within this limitation. With these parameters the FDTD can be expected to converge to the correct SAR.

Orientation of the object is defined by the incident-field vectors: E (electric field measured in V/m); H (magnetic field measured in A/m); and K (direction of propagation)—parallel to the long axis of the body. In this paper, we consider the dorsal (M) direction of propagation. Detailed description on different orientations is presented in Fig. 1. The model was processed in the far-field conditions at the resonant frequency (70 MHz) and above (200, 400, 918, and 2060 MHz) for MEHK orientation. In addition, other orientations (MKEH, MHEK) of the model to the incident fields were used where no substantial resonant frequency exists.

In the 3-mm-resolution man model, the permittivity values for all 39 tissue-types were altered simultaneously for each orientation and applied frequency. In addition, permittivity values for muscle, fat, skin, and bone marrow were manipulated independently. These selected tissues were those with the greatest variability in permittivity values, as reported by Hurt *et al.* [14] or

TABLE III
NORMALIZED WHOLE BODY SAR (W/kg/mW/cm^2) VALUES FOR A MAN MODEL FOR SELECTED FREQUENCIES IN RELATION TO THE DIFFERENT ORIENTATIONS AND RATIOS WHEN CHANGING PERMITTIVITY VALUES FOR MUSCLE ONLY

Orientation	Frequency (MHz)	Normalized whole body SAR (W/kg/mW/cm^2) (*)	Highest ratio (**)	Lowest Ratio (**)
MEHK	70	0.27	1.01	0.90
	200	0.05	0.85	1.17
	400	0.06	0.89	1.10
	918	0.06	0.98	1.03
	2060	0.05	1.07	0.96
MHEK	70	0.02	1.18	0.82
	200	0.03	0.88	1.16
	400	0.05	0.88	1.14
	918	0.06	0.97	1.00
	2060	0.06	1.05	0.97
MKEH	70	0.04	1.07	0.81
	200	0.04	0.86	1.17
	400	0.05	0.94	1.02
	918	0.03	1.00	0.97
	2060	0.02	1.14	0.91

with the highest percentage of content in the whole-body mass. The permittivity value assigned to a voxel was calculated from the four-term Cole–Cole fits published by Gabriel [1].

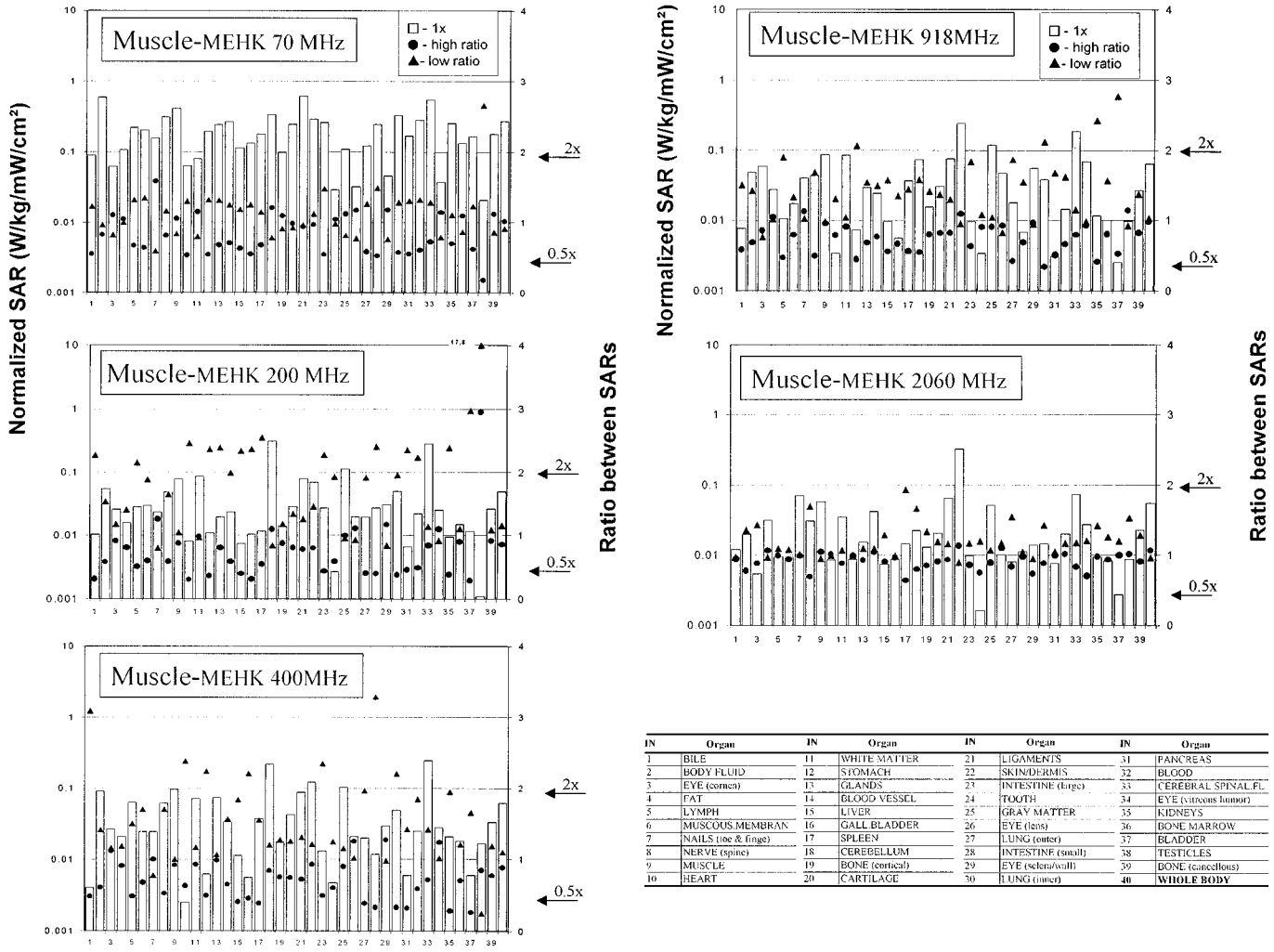
It is useful to consider the real part separately from the imaginary part of the complex permittivity. It is frequently argued that conductivity has major role in affecting the SAR value and distribution, particularly at lower frequencies. To test this hypothesis, analysis of SAR variations with respect to separate changes of the dielectric value or conductivity for only muscle were made. As presented in Table II, the ratios were either 0.5 times Gabriel's values, 2.0 times Gabriel's values, or the original values published by Gabriel [1]. This procedure discriminates the roles of the real and the imaginary part of the complex permittivity in determining SAR values. Manipulations of the other individual tissue types (fat, skin, bone marrow) were not taken into account since only minor changes in whole-body or localized SAR ratios were observed in the previous study. For the purposes of this study, a dual-processor personal computer (500 MHz) with a total of 1 GB of RAM was used.

III. RESULTS

A. Whole Body SAR

The normalized whole-body SAR (W/kg/mW/cm^2) values (SAR_{1x}) for the man (3-mm^3 voxel size) at a resonance frequency of 70 MHz, using the original permittivity values as reported by Gabriel [1], are the highest in the MEHK orientation (0.27 W/kg/mW/cm^2), lower for MKEH (0.04 W/kg/mW/cm^2), and lowest for MHEK (0.02 W/kg/mW/cm^2) (see Table III). These results are in good agreement with data published in RF Dosimetry Handbook [17]. When comparing our results with those obtained by normalized man (73 kg, height 1.76 m), slightly higher values (10%) on normalized whole-body SAR were presented [18].

When changing the permittivity values for muscle only, the whole-body SAR is not particularly sensitive. Ratios for normalized whole-body SAR calculated by changing the permittivity value of muscle only (lowest ratio equals 0.5-times the original value and highest ratio equals two times the original value) are also presented in Table III. The greatest deviation from unity in the ratio of whole-body SAR values (ratios $SAR_{highest}/SAR_{1x}$ or SAR_{lowest}/SAR_{1x}) was observed



IN	Organ	IN	Organ	IN	Organ	IN	Organ
1	BILE	11	WHITE MATTER	21	LIGAMENTS	31	PANCREAS
2	BODY FLUID	12	STOMACH	22	SKIN/DERMIS	32	BLOOD
3	EYE (cornea)	13	GLANDS	23	INTESTINE (large)	33	CEREBRAL SPINAL FL.
4	FAT	14	BLOOD VESSEL	24	TOOTH	34	EYE (vitreous humor)
5	LYMPH	15	LIVER	25	GRAY MATTER	35	KIDNEYS
6	MUSCOUS MEMBRAN	16	GALL BLADDER	26	EYE (lens)	36	BONE MARROW
7	NAILS (toe & finge)	17	SPLEEN	27	LUNG (outer)	37	BLADDER
8	NERVE (spine)	18	CEREBELLUM	28	INTESTINE (small)	38	TESTICLES
9	MUSCLE	19	BONE (cortical)	29	EYE (sclera/wall)	39	BONE (cancellous)
10	HEART	20	CARTILAGE	30	LUNG (inner)	40	WHOLE BODY

Fig. 2. Normalized SAR values (W/kg/mW/cm^2) and ratios between different SAR values for each organ obtained by changing the permittivity value for muscle only either 0.5 times Gabriel's values (SAR_{low}) or 2.0 times Gabriel's values (SAR_{high}). Columns represent normalized SAR values (left ordinate) and "• and ▲" represent ratio values (right ordinate). Numbers on abscissa correspond to identification number (IN) of tissue type in first column of adjacent table.

at MKEH orientation (ratio 0.81, see Table III), at 70 MHz. At the other frequencies (200, 400, 918, and 2060 MHz), the ratios of the whole-body SAR values when changing the permittivity values for muscle at all orientations were closer to the unity. At other applied orientations and frequencies, uncertainties in permittivity for muscle (see Table II) resulted in whole-body SAR values that were within $\pm 20\%$.

The ratios of whole-body SARs by changing all tissue types simultaneously or varying other tissues one at a time (bone marrow, skin, and fat) for MEHK orientation are shown in Table IV. When changing original permittivity of all tissue types of the human anatomical model (39 tissue types) by either 0.5 times Gabriel's values (SAR_{lowest}), or 2.0 times Gabriel's values ($SAR_{highest}$) the whole-body SAR ratios remain within 20%. When changing permittivity of individual tissue type that represents a significant proportion of the body mass (fat 29%, skin 5%) or considered as extreme outliers (bone marrow) by corresponding factor (see Table IV) the whole-body SAR ratios remain also within 20%. At 2060 MHz, the deviation from unity for the whole-body SAR ratio (SAR_{high}/SAR_{1x}) was the greatest (30%) when changing only skin in comparison to the all other frequencies or tissue types.

B. Localized SAR

In contrast to whole-body SAR values, the localized SAR values for individual organs are substantially influenced by variability in permittivity values. This was critical for tissue types which represent a significant proportion of the body mass (especially for muscle which represented 42% of the total body mass).

C. Changing Muscle Only

The largest deviation from unity (ratios SAR_{high}/SAR_{1x} and SAR_{low}/SAR_{1x}) in localized SAR values when changing permittivity for muscle was observed at 200 MHz at MEHK orientation (see Fig. 2). Over 40% of all tissue types (bile, lymph, heart, stomach, glands, blood, liver, spleen, intestine, lung, pancreas, kidney, and bladder) resulted in localized SAR ratios higher than 2.0 or lower than 0.5 when compare to

TABLE IV
NORMALIZED WHOLE BODY SAR (W/kg/mW/cm^2) VALUES FOR A MAN MODEL FOR SELECTED FREQUENCIES WHEN CHANGING PERMITTIVITY VALUES FOR ALL TISSUE TYPES, OR CHANGING INDEPENDENTLY FAT, SKIN, AND BONE MARROW

Orientation	Frequency (MHz)	Normalized SAR (*)	All tissue types		Fat		Skin		Bone Marrow
			Ratio high (**)	Ratio low (**)	Ratio high (**)	Ratio low (**)	Ratio high (**)	Ratio low (**)	Ratio high (**)
MEHK	70	0.27	0.98	0.83	1.03	0.99	1.01	1.00	1.01
	200	0.05	0.88	1.13	1.01	1.02	1.08	1.00	1.02
	400	0.06	0.92	1.07	0.98	0.97	1.03	0.97	1.02
	918	0.06	0.89	1.05	0.89	1.02	0.88	0.98	0.99
	2060	0.05	0.81	1.19	0.90	1.08	0.70	1.14	1.02

original values ($1x$). An extreme ratio (17.8-fold increase in localized SAR) was found for testicles.

At all other applied frequencies, only a few tissue types were changed, more than 2.0 or less than 0.5. At 70 MHz, only 2% (testicles, intestine) of all tissue types were changed substantially; at 400 MHz, only 18% of all tissue types (bile, heart, stomach, liver, spleen, intestine, lung, pancreas, kidney, bladder, testicles) were substantially changed; at 918 MHz, only 10% (lymph, stomach, lung/inner and outer/, kidney, and bladder) of all tissue types were substantially changed; and at 2060 MHz, no tissue type changed more than 2.0 or less then 0.5.

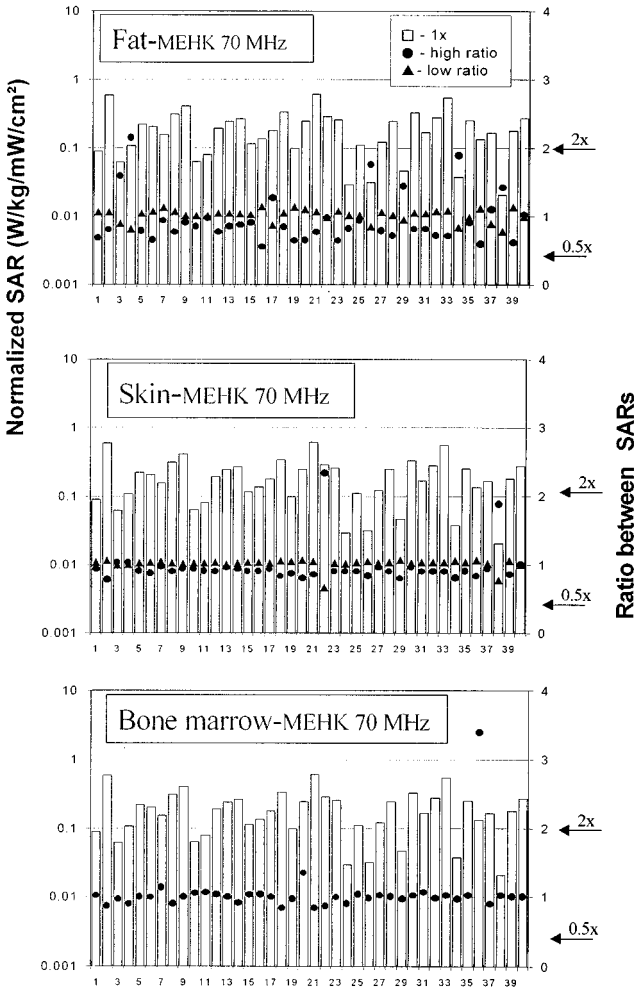
Similar patterns in localized SAR ratios were observed at MKEH orientation, where 25% (heart, stomach, liver, spleen, lung, intestine, pancreas, blood, kidney, testicles) of all tissue types changed more than 2.0 or less than 0.5 at 200 MHz (data not graphed). In contrast, at 2060 MHz all SAR ratios were less than 1.3 or more than 0.8. At H orientation, less that 10% of all tissue types resulted in localized SAR values higher than 2.0 or lower than 0.5 when compared with the original values ($1x$) at all applied frequencies.

D. Changing all Tissue Types

The greatest changes in localized SAR values (ratios $\mathrm{SAR_{highest}}/\mathrm{SAR}_{1x}$ and $\mathrm{SAR_{lowest}}/\mathrm{SAR}_{1x}$) when changing permittivity for all tissue types were observed at MEHK orientation at 200 MHz (data not graphed). Almost 50% (bile, lymph, mucous membrane, heart, stomach, glands, blood vessels, liver, spleen, intestine, lung, pancreas, blood, kidney, bladder, and testicles) of all tissue types resulted in localized SAR ratios higher than 2.0 or lower than 0.5 when compared with original values ($1x$). Almost 20% (bile, stomach, gallbladder, tooth, pancreas, bladder, and testicles) of all tissue types resulted in localized SAR ratios higher than 3.0. At other frequencies (400, 918 and 2060 MHz), less than 20% of all tissue types had localized SAR altered by more than 2.0 times. At resonant frequency (70 MHz), the variations were the least substantial and only a few tissue types (bile, heart, spleen, testicles) resulted in localized SAR ratios lower than 0.5.

E. Changing Other Tissue Types

Changing the permittivity values of fat or skin, which comprise 29% and 5% of total body mass, respectively, did not substantially influence localized SAR values. At 70 MHz, when changing the permittivity values for fat, substantial changes in ratios (over 2.0) of localized SAR were observed only in fat (see Fig. 3). Smaller ratios in localized SAR were observed for bladder, bone marrow, bone, eye (cornea, lens, sclera, vitreous



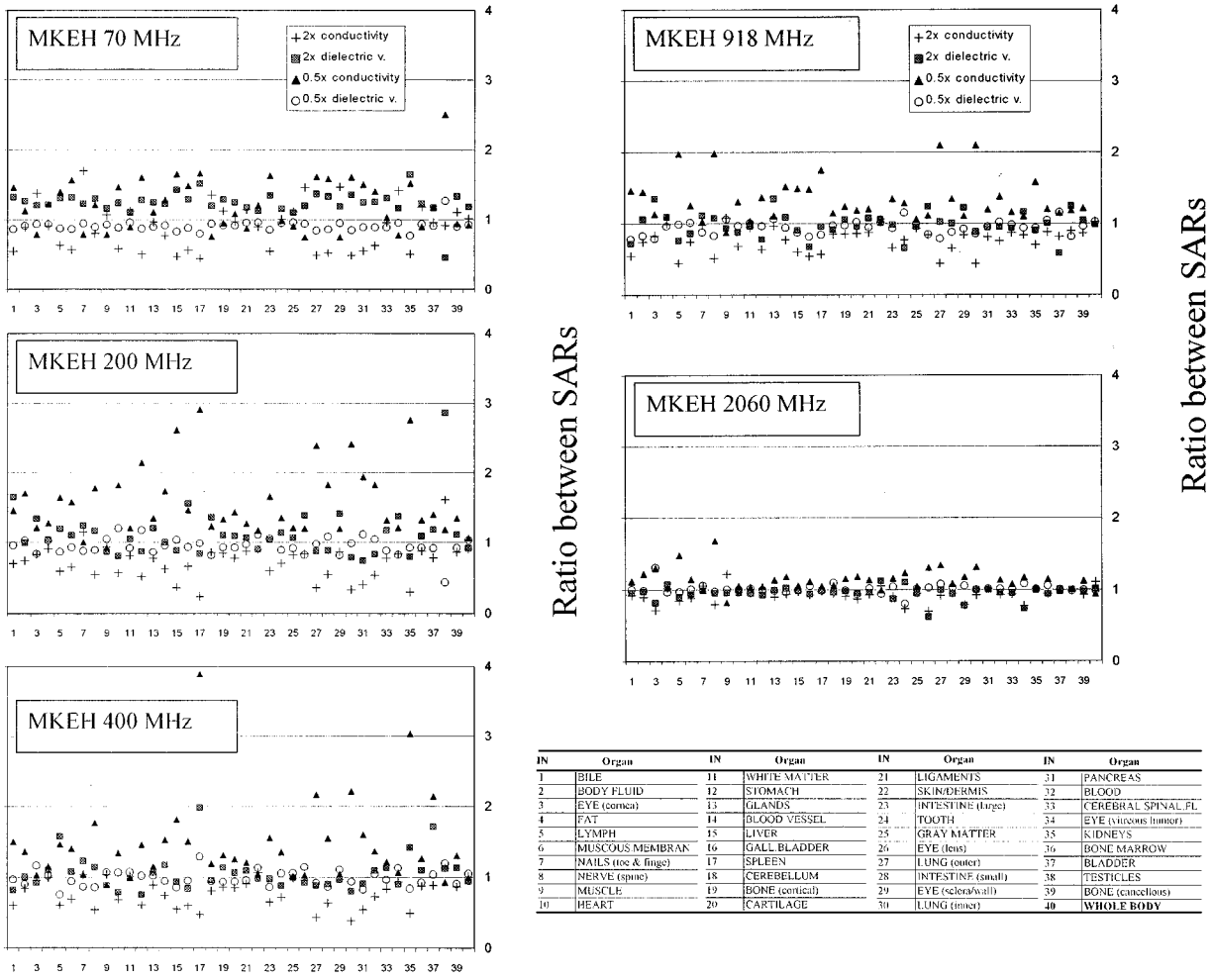
IN	Organ	IN	Organ	IN	Organ	IN	Organ
1	BILE	11	WHITE MATTER	21	LIGAMENTS	31	PANCREAS
2	BODY FLUID	12	STOMACH	22	SKIN/DERMIS	32	BLOOD
3	EYE (cornea)	13	GLANDS	23	INTESTINE (large)	33	CEREBRAL SPINAL FL
4	FAT	14	BLOOD VESSEL	24	TOOTH	34	EYE (vitreous humor)
5	LYMPH	15	LIVER	25	GRAY MATTER	35	KIDNEYS
6	MUSCOUS MEMBRAN	16	GALL BLADDER	26	EYE (lens)	36	BONE MARROW
7	NAILS (toe & finge)	17	SPLEEN	27	LUNG (outer)	37	BLADDER
8	NERVE (spine)	18	CEREBELLUM	28	INTESTINE (small)	38	TESTICLES
9	MUSCLE	19	BONE (cortical)	29	EYE (sclera/wall)	39	BONE (connections)
10	HEART	20	CARTILAGE	30	LUNG (inner)	40	WHOLE BODY

Fig. 3. Normalized SAR values (W/kg/mW/cm^2) and ratios between different SAR values for each organ obtained by changing the permittivity value for only fat, skin, and bone marrow. Columns represent normalized SAR values (left ordinate) and "• and ▲" represent ratio values (right ordinate). Numbers on abscissa correspond to the IN of tissue type in first column of adjacent table.

humor), and testicles. At other frequencies (not graphed), the localized SAR ratios ($\mathrm{SAR_{highest}}/\mathrm{SAR}_{1x}$ and $\mathrm{SAR_{lowest}}/\mathrm{SAR}_{1x}$) for above mentioned tissue types were within 2.0 or 0.5, while the ratios of localized SAR values for all other tissue types were very close to unity (within $\pm 10\%$).

When changing the permittivity values for skin, the only substantial ratio of localized SAR (2.4) was found for skin itself at 70 MHz in the MEHK orientation. For all the other tissue types (except testicles ratio 1.8) the SAR ratios were close to unity (see Fig. 3).

Bone marrow, which represents less than 3% of the total body mass, was chosen as tissue with the highest variability in reported permittivity values [10]. The numerical simulation clearly demonstrated that uncertainty in permittivity at 70 MHz for bone marrow influences substantially only the bone marrow



IN	Organ	IN	Organ	IN	Organ	IN	Organ
1	BILE	11	WHITE MATTER	21	LIGAMENTS	31	PANCREAS
2	BODY FLUID	12	STOMACH	22	SKIN/DERMIS	32	BLOOD
3	EYE (cornea)	13	GLANDS	23	INTESTINE (large)	33	CEREBRAL SPINAL FL
4	FAT	14	BLOOD VESSEL	24	TOOTH	34	EYE (vitreous humor)
5	LYMPH	15	LIVER	25	GRAY MATTER	35	KIDNEYS
6	MUSCOUS MEMBRAN	16	GALL BLADDER	26	EYE (lens)	36	BONE MARROW
7	NAILS (toe & finge)	17	SPLEEN	27	LUNG (outer)	37	BLADDER
8	NERVE (spine)	18	CEREBELLUM	28	INTESTINE (small)	38	TESTICLES
9	MUSCLE	19	BONE (cortical)	29	EYE (sclera/wall)	39	BONE (cancellous)
10	HEART	20	CARTILAGE	30	LUNG (inner)	40	WHOLE BODY

Fig. 4. Ratios between different localized SAR values for each organ obtained by changing the dielectric value and conductivity separately for muscle only (for high and low ratios for permittivity see Table II). Numbers on abscissa correspond to IN of tissue type in first column of adjacent table.

itself; the ratio was 3.4. The localized SAR ratios for all other tissue types were close to unity (see Fig. 3).

F. Changing Dielectric Value and Conductivity Separately

Changing the real part separately from the imaginary part of the complex permittivity gives more detailed information on which parameter has greater influence on SAR predictions and which one's accurate estimation is really critical. We analyzed whole-body and localized SAR ratios for MKEH orientation and different frequencies when changing dielectric value separately from conductivity of muscle only. It was shown that normalized whole-body SAR (IN 40 on abscissa) ratios for any combination of frequency or orientation were very close to unity.

In the contrast to the lack of the dependence of whole-body SAR on variability in conductivity or dielectric value, detailed investigation on localized SAR ratios showed that conductivity presents more substantial factor in absorption of RF energy in tissues than dielectric value for most of the applied frequencies. This was particularly demonstrated at 70, 200, and 400 MHz where ratios in localized SAR for stomach, liver, spleen, lung (inner and outer), kidneys, and bladders were greater than 2.0.

At higher frequencies (2060 MHz), this difference between conductivity and dielectric values became less substantial and both components-real and imaginary become equally important. Detailed localized SAR ratios for each organ obtained by changing the dielectric value and conductivity for muscle only for all applied frequencies for MKEH orientation are presented in Fig. 4.

IV. Discussion

This research examined the extent to which variation among in published permittivity values of biological materials influences SAR values (whole-body or localized in a particular target tissue). This work contributes to understanding the mechanisms of interaction of RF fields with biological systems and to the SAR dependence on variability in permittivity values, thus leading to increased understanding of the validity of numerical calculations.

The present work showed that uncertainty in permittivity values does not substantially influence whole-body SAR values, while localized SAR values are substantially affected by these variations. Whole body SAR ratios ($\mathrm{SAR}_{\mathrm{highest}}/\mathrm{SAR}_{1x}$ or $\mathrm{SAR}_{\mathrm{lowest}}/\mathrm{SAR}_{1x}$) in all three applied orientations (E, H, and

K) and five frequencies when taking into account the worst case conditions in relation to uncertainty in permittivity for any applied tissue (the highest and lowest ratios for permittivity values according to the published data for muscle, skin, fat, and bone marrow is presented in Table II) were within $\pm$20%. These observations are consistent with data in the RFR Dosimetry Handbook [17, Fig. 5.7] showing small changes in whole-body SAR when changing the permittivity of the muscle in a prolate spheroidal model of an average man. This appears to be generally true for frequencies above the resonant for adult man (70 MHz). The only exception where the uncertainty in permittivity resulted in greater whole-body SAR ratio ($\pm$30%), was found for skin at 2060 MHz. This is most likely because of the increased reflection coefficient on the boundary between skin/fat or skin/muscle. Since the voxel resolution of the 3-mm man model is relatively low, very small organs may be distorted or lost (skin), some symmetries may be affected, organs change mass slightly and the continuity of elongated structures may be disrupted. Therefore, the present data do not represent strong evidence for the notion that when changing the permittivity values of skin, greater amounts of incident RF energy might be reflected and therefore the whole-body SAR is changed.

As mentioned, uncertainties in permittivity had greater effect on localized SAR values when they were low compared to the whole-body SAR value or when errors involved tissues which represent a substantial proportion of the body mass (muscle). The effect was less substantial when manipulating other tissues (fat, skin, bone marrow). This is most likely because muscle tissue comprises the bulk of the mass of the man model. Muscle (high water content tissue) is more lossy than less wet tissues (fat, skin, bone) and, hence, absorbs more energy from EMFs. Changing the permittivity values of muscle by factor of two resulted in localized SAR ratio change by factor of two in almost 50% of all tissue types. Similar overall trends at all applied orientations were determined. Since muscle is spread through the whole human body, it forms complex multiple tissue layers and affects the localized SAR values in the majority of the surrounding tissues and organs. The reflection and transmission of the incident plane wave, which depend on the frequency, orientation, angle of incidence, and on permittivity of the tissue, determine the absorption characteristics of the biological structures. Therefore, changes in permittivity values of muscle not only cause change in localized SAR of the muscle but also indirectly affects localized SAR values of other surrounding tissues.

We found an extreme in localized SAR ratio for testicles (17.8-fold increase in localized SAR, see Fig. 3) at E orientation when increasing permittivity of muscle for factor of two. However, this might be due to extremely low absolute SAR value in that tissue type in comparison to all other organs and relatively low number of voxels (only 0.2% of the whole-body).

In addition, we changed the real part separately from the imaginary part of the complex permittivity to get more detailed information on which parameter might have greater influence on whole-body and localized SAR predictions. It is well known that RF electromagnetic energy is preferentially absorbed in the high-conductivity tissues (e.g., eye, brain, muscle) rather than in the low conductivity tissues (e.g., fat, bone, skull) [19]. However, interfaces between tissues with greatly different permittivity values might be influential on localized SAR values. The organs with rather low conductivity and low primary SAR values could gain absorbed energy from surrounding high-conductivity organs with high primary SAR values [20]. This might be one of the main obstacles for more detailed and apparent identification of the prevailing role of each component of the complex permittivity in SAR predictions. Thus, dielectric value or conductivity did not show any substantial contribution to changes in normalized whole-body SAR. On the other hand, a detailed analysis on real and imaginary part of the complex permittivity showed slightly prevalent role of conductivity on predictions of the localized SAR values. At specific frequencies and orientations, the difference between real and imaginary part became less significant. Accurate estimation of both components, dielectric value and conductivity, is crucial in SAR predictions in the man model.

EMFs standards and compliance to the standards are based, in part, on experimental data and the replication of these data. Therefore, accurate RF dosimetry is an essential component in designing, replicating, or confirming an experiment. To ensure compliance with safety guidelines during equipment design, manufacturing, and maintenance, realistic and accurate models could be used as a bridge between empirical data and actual exposure conditions. Before these tools are transitioned into the hands of health safety officers and designers, their sensitivity, accuracy, and limitations must be known in relation to the variability in different models' parameters including exposure conditions. Accurate predictions of localized and whole-body SAR values by computer models may lead to minimizing the safety margin and, therefore, to modification of existing safety standards. Furthermore, higher quality dosimetry will lead to more precise data that are critical in the harmonization of the EMF standards.

In our study, only far-field exposure conditions were considered. For near field exposure, varying the ratio between electric and magnetic field might lead to different results. It is expected that different digital anatomical models (different laboratory animal or sized man models) may show distinct variations in SAR values due to uncertainty in permittivity. Gajšek *et al.* [21] showed that predicted whole-body SAR values when using anatomical model of the rat are very sensitive to variability in permittivity and, thus, different from those obtained by man model. For more detailed analysis on permittivity versus SAR relationship, detailed interlaboratory comparison among the various anatomical models used by other research groups would be required. In doing so, the size of the model and quality of tissue identification must be considered. A model may have numerous tissue types identified, however, attention must be given to how well the structures of the identified tissues correspond to their anatomical realities. As of yet, comparing models could be a very hard task since only those models used by authors are freely available via the Internet (http://starview.brooks.af.mil/EMF).

In summary, since there is no universal approach to predicting the relative changes in localized SAR values, the relationship between variations in permittivity (dielectric value and conductivity) and localized SAR for each case (orientation, frequency, tissue type, exposure conditions) must be validated.

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