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Debye Constants for Biological Tissues From 30 Hz to 20 GHz

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Abstract- Debye modeling for the dielectric properties of dispersive materials facilitates its incorporation into the FDTD formulation. This paper generates a comprehensive list of multi-term Debye coefficients for 16 biological tissues. A numerical technique is developed to accurately fit one, two, and three-term Debye equations with the published experimental data of biological tissues. Using the generated coefficients, the reconstructed complex permittivity is shown to be in excellent agreement with the corresponding measured data over the frequency range 30 Hz to 20 GHz.

I. INTRODUCTION

Several methods have been used for calculation of EM energy absorbed in human tissues. A review of theoretical and numerical dosimetry techniques has been introduced in [1]. Among the different numerical techniques, the FD-TD has proven to be extremely useful to calculate the induced currents and fields in the human body or head exposed to electromagnetic radiation [2-10]. The dispersive properties of the human tissues have not been considered while calculating the specific absorption rate (SAR) in [2-3]. On the other hand, the time-domain susceptibility function is convolved with the electric field, and incorporated into the basic Yee algorithm to produce the dispersive FDTD formulation in [4]. This formulation has been modified in [5] to obtain broadband frequency information in 3D biological applications. A simpler differential equation approach is developed and implemented for general dispersive media in [6-8] that requires the representation of the dielectric properties of biological tissues in Debye form. Two terms Debye equations were used in [4-8], because three-term debye requires more computer storage and CPU time. Furthermore, the relaxation constant values were held constant in the FDTD simulations models presented in [4-8] to reduce the computational time and complexity. However, as noted in [8], the accuracy of the specific absorption rate (SAR) calculations was proportional to the accuracy of the material properties predicted by Debye equation.

The dielectric properties (the dielectric constant and the loss factor) of biological materials in the frequency range 10 kHz to 10 GHz are collected and tabulated in [11]. An extended collection of the complex permittivity from the past five decades are presented in a graphical format in [12]. Three experimental techniques were used to measure the dielectric properties of animal and human tissues in the frequency range 10Hz to 20GHz, and the measured results are plotted in [13]. A parametric model based on the Cole-Cole formulation was used in [14] to fit these measured data.

Although, Cole-Cole provides a better physical model than Debye for material properties as a function of frequency, it is more cumbersome to program in a FDTD algorithm. Debye modeling of dispersive materials is therefore, recommended for dispersive FDTD formulation. Hurt developed a numerical procedure to fit a five-term Debye equation to the published permittivity data for muscle [15]. Recently, the two-term Debye coefficients for biological tissues were obtained by a least square fit procedure [7] to match the measured data up to 1500 MHz. Debye parameters (three term in addition to the imaginary ionic conductivity term) are also obtained and tabulated in [16] to fit the experimental data with an approximate error of 15% in the frequency range 0.75 to 250 MHz.

In this paper, a numerical procedure is developed to obtain the two and three terms Debye coefficients to accurately fit the experimental data for the biological tissues in the frequency range 30 Hz to 20 GHz. For accurate fitting of the experimental data, this wide frequency range is divided into four overlapping sub ranges, namely from 30Hz to 1.1kHz, from 1 kHz to 200kHz, from 150kHz to 550MHz, and from 500 MHz to 20GHz. The errors in the tabulated data for the 16 different biological tissues do not exceed 4% at any frequency based on the three term Debye expression.

II- FORMULATION

For dielectric dispersive media, the flux density vector $\vec{D}$ is related to the electric field intensity vector $\vec{E}$ through the complex permittivity $\varepsilon^*(\omega)$ by

$$\vec{D}(\omega) = \varepsilon^*(\omega)\vec{E}(\omega) \quad (1)$$

The general form of Debye formulation for the relative complex permittivity $\varepsilon_r^*(\omega)$ is given in [16] as

$$\varepsilon_r^*(\omega) = \varepsilon_\infty + \frac{\sigma_i}{j\omega\varepsilon_o} + (\varepsilon_s - \varepsilon_\infty)\sum_{n=1}^{N}\frac{A_n}{1+j\omega\tau_n} \quad (2)$$

Where ε_∞ is the relative permittivity at $\omega\tau_n >> 1$, ε_s is the relative permittivity at $\omega\tau_n << 1$, and σ_i is the static ionic conductivity. Using the "*residues*" Matlab procedure, the Debye coefficients $(\varepsilon_s, \sigma_i, A_n, \tau_n)$ were obtained and tabulated in [16]. The reported three-term Debye coefficients, in addition to the ionic conductivity term, are obtained in the frequency range 0.75 to 250 MHz with error not exceeding 15%. However, the ionic conductivity term $\frac{\sigma_i}{j\omega\varepsilon_o}$ will complicate the auxiliary differential equation (ADE) approach for dispersive FDTD formulation [6-8].

This paper adopts a more convenient Debye formulation, in which σ_i is implicitly considered such that

$$\varepsilon_r^*(\omega) = \varepsilon'_\infty + \sum_{n=1}^{N}\frac{\Delta\varepsilon'_n}{1+j\omega\tau'_n} \quad (3)$$

Where $\Delta\varepsilon'_n = A'_n(\varepsilon'_s - \varepsilon'_\infty)$, ε'_s and ε'_∞ represent the values of the relative permittivity at very low and very high frequencies, respectively, and N is the order (number of terms) of the Debye relation. The procedure is based on substituting the experimental data of [13] in the L.H.S. of (3), and then using a two-step numerical fitting procedure to yield the required Debye Coefficients $(\varepsilon'_\infty, \Delta\varepsilon'_n, \tau'_n)$. First, the Matlab "*invfreqs*" function is used to find the real coefficients of the numerator *b(nb+1)* and denominator *a(na+1)* of the measured $\varepsilon_r^*(\omega)$ as described in the following form.

$$\varepsilon_r^*(j\omega) = \frac{b(1)(j\omega)^{nb} + b(2)(j\omega)^{nb-1} + \ldots + b(nb+1)}{a(1)(j\omega)^{na} + a(2)(j\omega)^{na-1} + \ldots + a(na+1)} \quad (4)$$

where in this analysis $na = nb = N$. The Matlab "*residue*" function is then used to convert the resulting quotient of the polynomial form of (4) to the partial function expansion, from which the corresponding Debye coefficients of (3) are calculated. The coefficients obtained are then substituted into the R.H.S. of (3) to reconstruct $\varepsilon_r^*(\omega)$, which is compared with the experimental data over the frequency range 30 Hz to 20 GHz. The maximum errors in the real and imaginary parts are also calculated and presented along with the two and three term Debye coefficients for the 16 biological tissues in 8 tables and 4 graphs covering the frequency range from 30 Hz to 20 GHz.

III. RESULTS AND DISCUSSIONS

Starting at the frequency band 30Hz to 1.1kHz, the two and three-term Debye coefficients are generated in Tables I and II; respectively. The maximum percentage errors in the real and imaginary parts of the reconstructed $\varepsilon_r^*(\omega)$ are calculated and presented. The complete set of comparison figures are also generated. Figure 1 clearly shows good coincidence between the generated $\varepsilon_r^*(\omega)$ using the 3-term Debye equation (D3), and the measured one represented by the 4-term Cole-Cole [14] formulation (C4) for the worst-fit case (liver tissues). The maximum errors for the two and three terms formulation do not exceed 18.57% and 3.31%, respectively, and the deviation from the measured data occurs only for the first few Hertz. The two-term Debye (D2) data is also compared with the measured data. The blood and dry skin tissues are modeled with less accuracy by the 4-term Cole-Cole formulation in [14], which may explain the peculiar results obtained for those tissues.

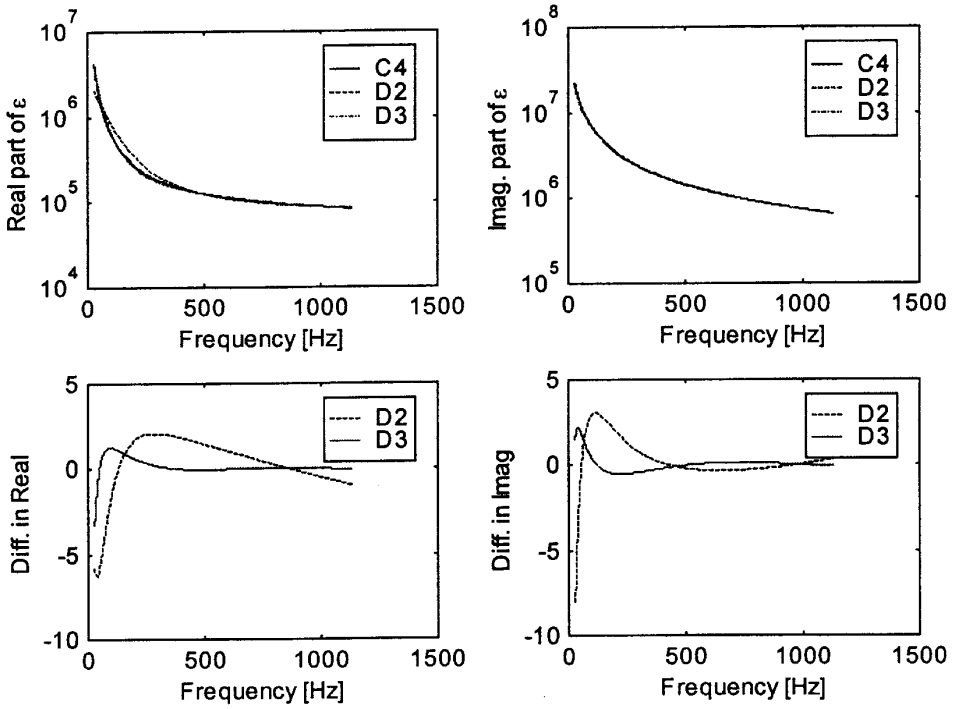

Fig. 1. Relative complex permittivity for liver tissue for the frequency band 30 Hz to 1100 Hz.

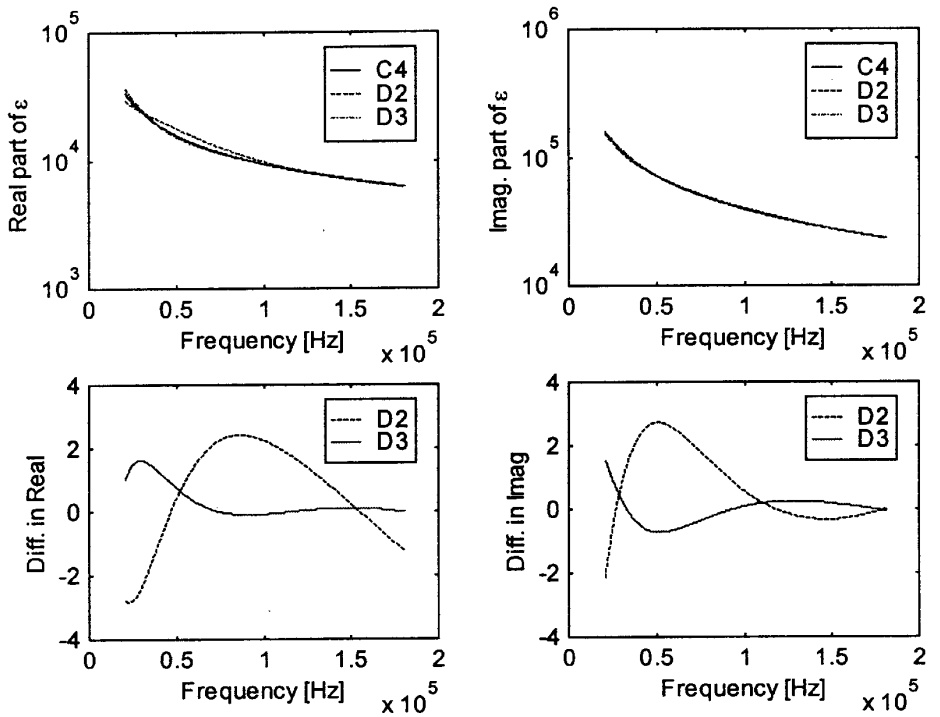

Fig. 2. Relative complex permittivity for heart tissue for the frequency band 1 kHz to 200 kHz.

Table (I) Two-term Debye parameters for the frequency range 30 Hz to 1100 Hz.

Tissue	ε'_∞	$\Delta\varepsilon'_1$	$\Delta\varepsilon'_2$	τ'_1 [s]	τ'_2 [s]	Max. % error in Real	Max. % error in Img.
Blood	5.260 e+003	3.316 e+003	-1.128 e+015	2.271 e-002	-1.426 e+004	0.00	0.00
Bone (cancellous)	1.143 e+004	3.193 e+006	2.729 e+010	5.057 e-003	3.181 e+000	1.80	0.69
Bone (cortical)	9.139 e+002	4.535 e+003	1.537 e+011	1.545 e-004	6.788 e+001	0.02	0.08
Brain (white matter)	5.458 e+004	1.169 e+007	9.855 e+008	3.705 e-003	2.534 e-001	9.80	7.21
Brain (grey matter)	1.436 e+005	1.863 e+007	8.886 e+008	3.024 e-003	1.779 e-001	10.42	16.65
Fat (infiltrated)	2.706 e+003	2.217 e+006	1.381 e+010	5.887 e-003	3.256 e+000	1.68	0.71
Fat (not infiltrated)	3.876 e+003	5.214 e+006	1.248 e+009	5.071 e-003	8.828 e-001	5.38	2.28
Heart	3.696 e+005	5.726 e+006	5.185 e+009	1.625 e-003	6.197 e-001	6.13	22.02
Kidney	*2.046 e+005*	*1.191 e+007*	*7.223 e+009*	*2.483 e-003*	*9.161 e-001*	*5.59*	*16.06*
Lens	8.378 e+004	7.666 e+005	1.140 e+011	7.705 e-004	3.168 e+000	0.79	1.64
Liver	7.571 e+004	1.661 e+006	8.839 e+008	1.832 e-003	2.366 e-001	6.27	7.95
Lung (inflated)	1.307 e+005	4.278 e+006	1.088 e+009	1.690 e-003	1.673 e-001	10.06	18.57
Muscle	1.736 e+005	1.087 e+007	3.664 e+010	9.984 e-004	1.419 e+000	6.42	9.91
Skin (wet)	3.111 e+004	1.436 e+004	3.051 e+007	5.852 e-004	1.081 e+000	12.97	16.07
Skin (dry)	1.134 e+003	1.901 e+000	-1.201 e+013	1.514 e-005	-2.659 e+005	0.00	0.00
Spleen	7.430 e+004	1.596 e+007	1.199 e+009	2.950 e-003	1.899 e-001	11.47	13.04

Another set of two and three-term Debye coefficients with the calculated maximum percentage errors are generated in Tables III and IV to cover the VLF and LF bands (1kHz to 200kHz). The worst fit case is for heart tissues and is plotted in Fig. 2. The maximum percentage errors for the two and three terms formulation do not exceed 6.36 and 1.64, respectively.

Table (II) Three-term Debye parameters for the frequency range 30 Hz to 1100 Hz.

Tissue	ε'_∞	$\Delta\varepsilon'_1$	$\Delta\varepsilon'_2$	$\Delta\varepsilon'_3$	τ'_1 [s]	τ'_2 [s]	τ'_3 [s]	Max.% error in Real	Max.% error in Img
Blood	5.260 e+003	- 2.529 e+001	2.739 e+001	- 4.021 e+019	- 5.938 e-004	6.318 e-004	- 5.086 e+008	0.00	0.00
Bone (cancellous)	2.179 e+003	1.781 e+004	1.948 e+007	3.150 e+012	1.342 e-004	1.568 e-002	3.976 e+002	0.01	0.01
Bone (cortical)	6.559 e+002	4.450 e+003	3.621 e+004	1.178 e+012	1.342 e-004	8.625 e-003	5.209 e+002	0.01	0.01
Brain (white matter)	3.133 e+004	5.795 e+004	2.675 e+007	3.603 e+009	1.629 e-004	6.368 e-003	1.344 e+000	2.55	1.18
Brain (grey matter)	2.285 e+004	1.765 e+005	4.477 e+007	2.655 e+011	9.112 e-005	5.288 e-003	1.165 e+002	0.08	0.08
Fat (infiltrated)	6.948 e+002	6.271 e+003	7.411 e+006	5.637 e+010	1.985 e-004	1.274 e-002	1.402 e+001	0.18	0.25
Fat (not infiltrated)	1.166 e+003	9.694 e+003	8.882 e+006	6.178 e+009	2.135 e-004	7.190 e-003	5.234 e+000	0.89	0.49
Heart	5.400 e+004	3.966 e+005	2.486 e+007	3.212 e+012	6.325 e-005	4.531 e-003	5.674 e+002	0.03	0.08
Kidney	3.257 e+004	2.205 e+005	2.990 e+007	4.126 e+012	6.934 e-005	4.537 e-003	7.294 e+002	0.02	0.06
Lens	1.016 e+004	1.892 e+005	3.700 e+007	9.513 e+012	1.461 e-004	1.521 e-002	2.800 e+002	0.02	0.01
Liver	5.631 e+004	6.336 e+004	9.616 e+006	2.018 e+009	1.878 e-004	6.540 e-003	6.742 e-001	3.31	2.24
Lung (inflated)	2.363 e+004	2.224 e+005	3.845 e+007	9.791 e+010	1.340 e-004	7.767 e-003	2.817 e+001	0.30	0.13
Muscle	4.342 e+004	1.016 e+006	2.406 e+007	1.392 e+012	2.623 e-004	2.175 e-003	6.116 e+001	0.20	0.54
Skin (wet)	3.011 e+004	2.300 e+003	2.349 e+004	2.056 e+008	1.111 e-004	1.090 e-003	8.649 e+000	1.85	3.55
Skin (dry)	1.136 e+003	- 4.868 e-001	3.463 e-001	- 8.857 e+015	- 6.494 e-005	8.012 e-004	- 1.961 e+008	0.00	0.00
Spleen	2.273 e+004	1.628 e+005	4.783 e+007	4.296 e+010	1.917 e-004	6.180 e-003	1.216 e+001	0.56	0.26

The third group of Debye parameters are presented in Tables V and VI to cover the MF, HF and VHF bands (150kHz to 550MHz), which is the largest subdivision band, and hence relatively the largest deviation errors are noticed in Tables V and VI.

Table (III) Two-term Debye parameters for the frequency range 1kHz to 200kHz.

Tissue	ε'_∞	$\Delta\varepsilon'_1$	$\Delta\varepsilon'_2$	τ'_1[s]	τ'_2[s]	Max. % error in Real	Max. % error in Img.
Blood	3.324 e+002	4.928 e+003	5.610 e+014	1.259 e-007	7.096 e+003	0.00	0.00
Bone (cancellous)	3.639 e+002	4.453 e+002	9.034 e+007	2.498 e-006	9.657 e-003	0.14	0.17
Bone (cortical)	1.963 e+002	1.065 e+002	2.379 e+007	1.960 e-006	1.027 e-002	0.18	0.24
Brain (white matter)	8.694 e+002	5.138 e+003	7.702 e+006	2.855 e-006	9.501 e-004	1.54	1.49
Brain (grey matter)	1.428 e+003	7.745 e+003	9.490 e+006	2.956 e-006	7.125 e-004	1.39	1.36
Fat (infiltrated)	5.256 e+001	9.576 e+001	9.134 e+007	3.730 e-006	1.966 e-002	0.05	0.05
Fat (not infiltrated)	3.181 e+001	1.699 e+002	1.292 e+007	3.693 e-006	5.200 e-003	0.16	0.15
Heart	4.087 e+003	2.370 e+004	4.657 e+006	2.883 e-006	2.464 e-004	2.84	2.73
Kidney	4.594 e+003	1.172 e+004	8.379 e+006	2.473 e-006	5.109 e-004	2.04	2.16
Lens	1.653 e+003	2.116 e+003	2.109 e+008	3.021 e-006	5.560 e-003	0.20	0.21
Liver	3.891 e+003	9.565 e+003	1.997 e+006	1.582 e-006	2.881 e-004	4.11	6.36
Lung (inflated)	1.217 e+003	5.719 e+003	7.921 e+006	2.851 e-006	7.361 e-004	1.22	1.28
Muscle	4.306 e+003	6.647 e+003	5.869 e+007	1.070 e-006	1.508 e-003	0.47	0.82
Skin (wet)	2.164 e+003	2.726 e+004	6.625 e+003	1.328 e-006	2.261 e-005	0.76	3.35
Skin (dry)	1.582 e+002	9.778 e+002	1.447 e+011	2.923 e-008	3.203 e+003	0.00	0.00
Spleen	3.057 e+003	3.864 e+003	1.899 e+007	2.248 e-006	1.490 e-003	0.83	1.14

The worst-fit case is also picked and displayed in Fig. 3 for spleen tissues, where the maximum errors for the two and three terms formulation are equal to 9.83% and 3.90%, respectively. The smallest subdivision band (0.5GHz to 20GHz) is proposed for the last group of Debye parameters, where the smallest deviation errors are obtained as expected in tables VII and VIII. The relative complex permittivity for kidney tissues is plotted in Fig. 4, where the worst fit is obtained with maximum percentage deviation for the two and three terms formulation of 5.24% and 0.8%, respectively.

Table (IV) Three-term Debye parameters the frequency range 1 kHz to 200 kHz.

Tissue	ε'_∞	$\Delta\varepsilon'_1$	$\Delta\varepsilon'_2$	$\Delta\varepsilon'_3$	τ'_1 [s]	τ'_2 [s]	τ'_3 [s]	Max. % eror in Real	Max. % eror in Img.
Blood	3.495 e+002	4.911 e+003	-8.638 e-001	5.234 e+013	1.263 e-007	-6.196 e-007	6.620 e+002	0.00	0.00
Bone (cancellous)	3.093 e+002	1.620 e+002	1.152 e+003	1.333 e+008	7.314 e-007	8.997 e-006	1.433 e-002	0.09	0.08
Bone (cortical)	1.645 e+002	6.259 e+001	2.660 e+002	3.603 e+007	4.810 e-007	8.141 e-006	1.565 e-002	0.10	0.09
Brain (white matter)	5.713 e+002	1.553 e+003	1.282 e+004	1.365 e+007	1.039 e-006	9.434 e-006	1.795 e-003	0.70	0.76
Brain (grey matter)	1.012 e+003	2.317 e+003	2.151 e+004	1.446 e+007	1.088 e-006	1.047 e-005	1.157 e-003	0.74	0.74
Fat (infiltrated)	4.885 e+001	2.041 e+001	2.934 e+002	1.242 e+008	1.163 e-006	1.247 e-005	2.679 e-002	0.03	0.02
Fat (not infiltrated)	2.597 e+001	3.720 e+001	4.837 e+002	1.642 e+007	1.238 e-006	1.184 e-005	6.649 e-003	0.08	0.07
Heart	2.613 e+003	7.163 e+003	7.074 e+004	7.622 e+006	1.010 e-006	1.046 e-005	4.760 e-004	1.64	1.53
Kidney	3.134 e+003	4.380 e+003	3.321 e+004	1.347 e+007	7.367 e-007	9.439 e-006	9.027 e-004	1.20	1.16
Lens	1.382 e+003	6.598 e+002	8.289 e+003	3.033 e+008	6.845 e-007	1.309 e-005	8.062 e-003	0.13	0.09
Liver	1.421 e+003	6.667 e+003	2.668 e+004	5.097 e+006	5.817 e-007	9.042 e-006	9.410 e-004	1.29	1.77
Lung (inflated)	8.766 e+002	1.749 e+003	1.496 e+004	1.149 e+007	1.032 e-006	9.794 e-006	1.130 e-003	0.71	0.70
Muscle	1.423 e+003	6.941 e+003	1.300 e+004	7.275 e+007	4.351 e-007	8.117 e-006	1.910 e-003	0.21	0.29
Skin (wet)	1.066 e+003	4.203 e+003	2.513 e+004	1.962 e+004	5.215 e-007	1.509 e-006	2.634 e-004	0.12	0.04
Skin (dry)	1.583 e+002	9.777 e+002	-5.229 e-003	2.606 e+008	2.923 e-008	-8.424 e-006	5.769 e+000	0.00	0.00
Spleen	2.571 e+003	1.536 e+003	8.124 e+003	2.659 e+007	7.252 e-007	7.347 e-006	2.150 e-003	0.47	0.41

IV. CONCLUSION

A numerical procedure is used to generate a multi-term Debye coefficients for biological tissues. Tables of the Debye coefficients (two and three terms) with maximum percentage errors are presented for the biological tissues from 30 Hz to 20 GHz. Based on the tabulated data, a complete set of comparison figures have been generated to guarantee the coincidence between the measured and reconstructed $\varepsilon_r^*(\omega)$ over the frequency range 30Hz to 20GHz. The picked examples for the worst-case fit have shown good coincidence between the measured $\varepsilon_r^*(\omega)$ and the reconstructed $\varepsilon_r^*(\omega)$ using three-term Debye coefficients, except at the starting edge of each selected frequency band, where very small deviation from the measured data is noticed. Higher order Debye equations are recommended for wider frequency bands than those presented in this paper. The technique presented is also valid for generating those coefficients.

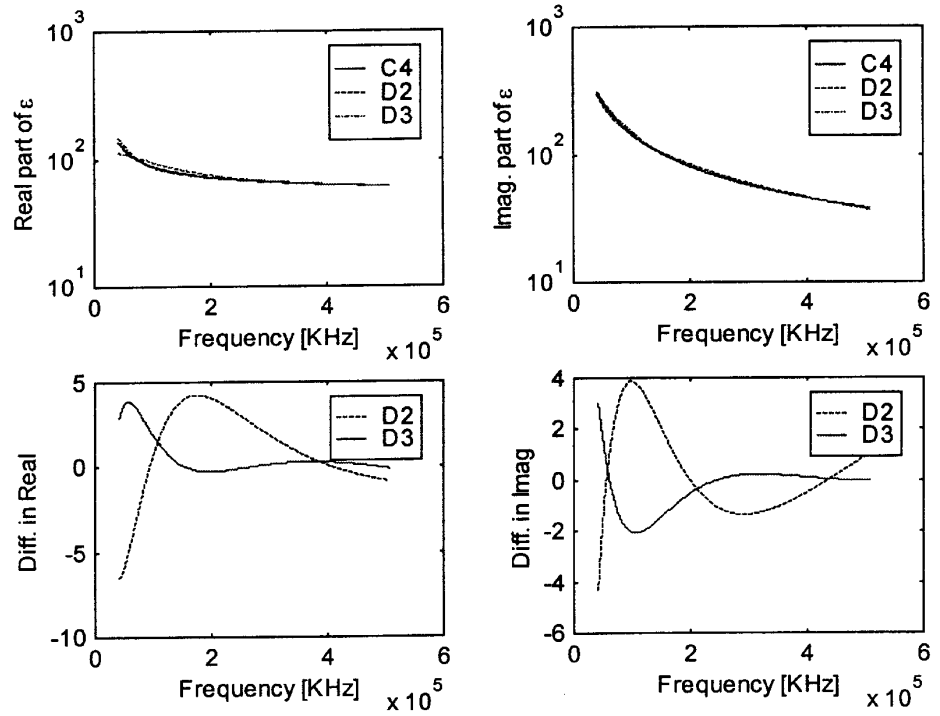

Fig. 3. Relative complex permittivity for spleen tissue for the frequency band 150 kHz to 550 MHz.

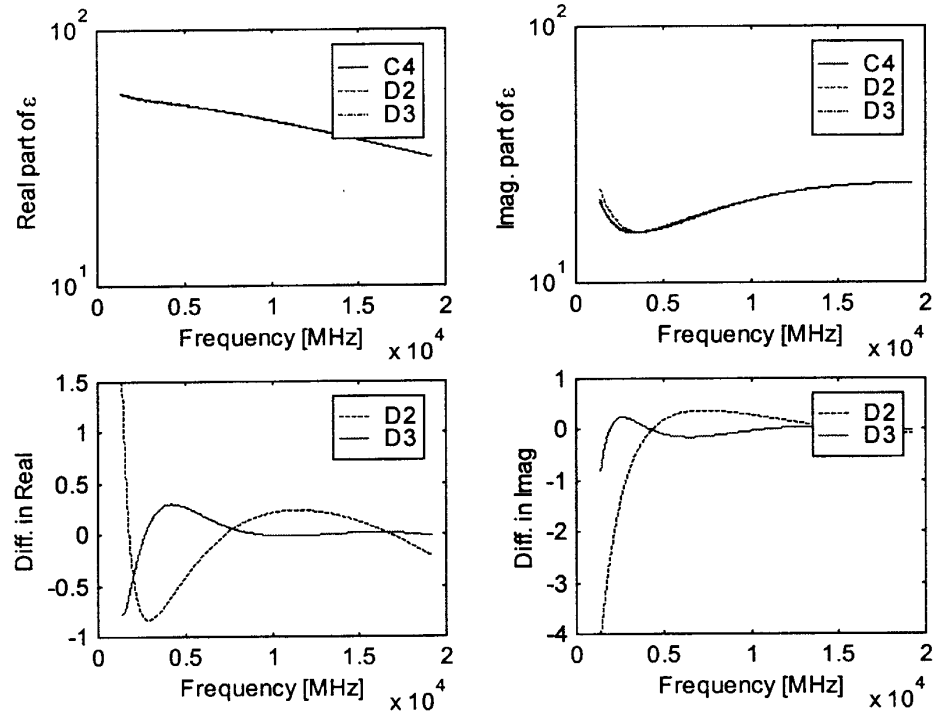

Fig. 4. Relative complex permittivity for kidney tissue for the frequency band 500 MHz to 20 GHz.

Table (V) Two-term Debye parameters for the frequency range 150 kHz to 550 MHz.

Tissue	ε'_∞	$\Delta\varepsilon'_1$	$\Delta\varepsilon'_2$	τ'_1 [s]	τ'_2 [s]	Max. % error in Real	Max. % error in Img.
Blood	6.179 e+001	3.266 e+001	4.036 e+007	1.358 e-009	3.120 e-004	2.24	1.77
Bone (Cancellous)	2.134 e+001	8.346 e+000	3.424 e+006	8.323 e-010	2.002 e-004	3.27	6.28
Bone (Cortical)	1.273 e+001	3.545 e+000	4.533 e+005	8.471 e-010	7.277 e-005	4.16	5.76
Brain White matter)	3.899 e+001	3.171 e+001	7.100 e+005	1.215 e-009	2.672 e-005	9.83	7.26
Brain (Grey matter)	5.299 e+001	5.288 e+001	1.101 e+006	1.344 e-009	2.327 e-005	9.12	4.74
Fat (Infiltrated)	1.156 e+001	2.994 e+000	4.598 e+006	1.629 e-009	7.016 e-004	3.44	1.84
Fat (not Infiltrated)	5.536 e+000	1.436 e+000	1.769 e+006	1.772 e-009	5.260 e-004	3.15	1.73
Heart	5.958 e+001	4.606 e+001	9.550 e+005	9.625 e-010	1.410 e-005	4.66	7.06
Kidney	5.831 e+001	5.869 e+001	9.179 e+005	9.915 e-010	1.261 e-005	5.59	7.60
Lens	4.685 e+001	1.800 e+001	1.544 e+007	1.343 e-009	2.472 e-004	2.58	1.88
Liver	4.664 e+001	3.279 e+001	2.069 e+005	9.655 e-010	4.651 e-006	5.10	7.30
Lung (Inflated)	2.205 e+001	1.661 e+001	1.075 e+006	1.141 e-009	3.689 e-005	4.21	4.36
Muscle	5.515 e+001	1.870 e+001	8.246 e+006	1.090 e-009	1.114 e-004	2.09	2.45
Skin (Wet)	4.592 e+001	2.942 e+001	2.173 e+004	9.850 e-010	4.388 e-007	4.05	6.48
Skin (Dry)	3.981 e+001	2.726 e+001	9.717 e+002	7.354 e-010	1.908 e-008	2.13	6.89
Spleen	5.744 e+001	6.069 e+001	7.686 e+005	1.241 e-009	1.074 e-005	6.54	4.31

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Table (VI) Three-term Debye parameters for the frequency range 150 kHz to 550MHz.

Tissue	ε'_∞	$\Delta\varepsilon'_1$	$\Delta\varepsilon'_2$	$\Delta\varepsilon'_3$	τ'_1[s]	τ'_2[s]	τ'_3[s]	Max. % error in Real	Max. % error in Img.
Blood	5.879 e+01	7.940 e+00	1.653 e+02	5.674 e+07	2.853 e-010	6.838 e-009	4.832 e-004	1.91	1.07
Bone(Cancellous)	1.986 e+01	3.665 e+00	2.169 e+01	4.819 e+06	2.290 e-010	3.305 e-009	3.320 e-004	2.37	1.91
Bone (Cortical)	1.194 e+01	1.673 e+00	1.081 e+01	6.563 e+05	2.027 e-010	3.778 e-009	1.317 e-004	2.85	2.02
Brain(white matter)	3.635 e+01	7.438 e+00	8.599 e+01	9.254 e+05	2.836 e-010	3.787 e-009	5.055 e-005	2.47	2.44
Brain (grey matter)	4.949 e+01	1.122 e+01	1.716 e+02	1.497 e+06	3.195 e-010	4.689 e-009	4.582 e-005	3.19	3.01
Fat (Infiltrated)	1.105 e+01	7.371 e-001	1.367 e+01	9.553 e+06	1.527 e-010	6.428 e-009	1.743 e-003	1.41	0.90
Fat (not Infiltrated)	5.380 e+00	2.550 e-001	6.106 e+00	2.584 e+06	1.897 e-010	6.419 e-009	8.866 e-004	1.26	0.82
Heart	5.546 e+01	1.547 e+01	1.137 e+02	1.054 e+06	3.135 e-010	3.384 e-009	1.897 e-005	2.59	2.38
Kidney	5.365 e+01	1.913 e+01	1.484 e+02	1.092 e+06	3.331 e-010	3.518 e-009	1.902 e-005	2.93	2.84
Lens	4.474 e+01	4.671 e+00	9.355 e+01	2.102 e+07	2.468 e-010	6.857 e-009	3.783 e-004	2.13	1.11
Liver	4.350 e+01	1.097 e+01	8.226 e+01	2.350 e+05	3.018 e-010	3.405 e-009	6.587 e-006	2.79	2.47
Lung (Inflated)	2.076 e+01	4.701 e+00	5.549 e+01	1.269 e+06	3.299 e-010	4.618 e-009	5.263 e-005	2.88	2.41
Muscle	5.287 e+01	5.931 e+00	6.843 e+01	9.356 e+06	2.624 e-010	4.810 e-009	1.382 e-004	1.82	1.21
Skin (wet)	4.319 e+01	9.406 e+00	7.311 e+01	2.406 e+04	3.002 e-010	3.334 e-009	5.787 e-007	2.21	1.91
Skin (dry)	3.695 e+01	1.108 e+01	5.333 e+01	1.025 e+03	2.772 e-010	2.150 e-009	2.450 e-008	1.21	0.83
Spleen	5.348 e+01	1.553 e+01	2.233 e+02	1.096 e+06	3.535 e-010	5.181 e-009	2.072 e-005	3.90	3.02

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Table (VII) Two-term Debye parameters for the frequency range 500 MHz to 20GHz.

Tissue	ε'_∞	$\Delta\varepsilon'_1$	$\Delta\varepsilon'_2$	τ'_1 [s]	τ'_2 [s]	Max. % error in Real	Max. % error in Img
Blood	6.680 e+000	5.355 e+001	4.064 e+002	7.838 e-012	2.404 e-009	0.32	1.97
Bone (Cancellous)	4.307 e+000	1.613 e+001	1.967 e+001	1.080 e-011	4.557 e-010	2.15	5.24
Bone (Cortical)	3.380 e+000	9.005 e+000	6.755 e+000	1.096 e-011	3.808 e-010	1.83	4.19
Brain White matter)	5.740 e+000	3.099 e+001	4.074 e+001	7.536 e-012	5.499 e-010	0.83	2.86
Brain (Grey matter)	6.366 e+000	4.341 e+001	7.959 e+001	7.526 e-012	6.937 e-010	0.66	2.85
Fat (Infiltrated)	3.396 e+000	8.082 e+000	1.669 e+001	6.912 e-012	1.635 e-009	0.19	1.72
Fat (not Infiltrated)	2.800 e+000	2.695 e+000	1.016 e+001	6.919 e-012	2.092 e-009	0.17	1.27
Heart	6.791 e+000	4.858 e+001	9.462 e+001	7.574 e-012	6.046 e-010	1.06	3.46
Kidney	6.781 e+000	4.600 e+001	1.025 e+002	7.627 e-012	5.587 e-010	1.50	3.99
Lens	6.008 e+000	4.009 e+001	1.805 e+002	7.447 e-012	2.137 e-009	0.25	1.63
Liver	6.023 e+000	3.782 e+001	6.345 e+001	8.329 e-012	5.954 e-010	0.92	3.21
Lung (Inflated)	3.453 e+000	1.737 e+001	4.781 e+001	7.533 e-012	8.721 e-010	0.57	2.87
Muscle	6.473 e+000	4.772 e+001	1.864 e+002	6.796 e-012	1.827 e-009	0.28	1.62
Skin (Wet)	6.038 e+000	3.760 e+001	7.488 e+001	7.524 e-012	7.337 e-010	0.61	2.81
Skin (Dry)	4.391 e+000	3.277 e+001	6.578 e+001	7.420 e-012	5.736 e-010	0.86	3.05
Spleen	6.618 e+000	4.649 e+001	1.149 e+002	7.559 e-012	7.290 e-010	0.85	3.31

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Table (VIII) Three-term Debye parameters for the frequency range 500 MHz to 20GHz.

Tissue	ε'_∞	$\Delta\varepsilon'_1$	$\Delta\varepsilon'_2$	$\Delta\varepsilon'_3$	τ'_1[s]	τ'_2[s]	τ'_3[s]	Max. % error in Real	Max % error in Img.
Blood	5.939 e+00	4.672 e+01	8.064 e+00	6.931 e+02	7.203 e-012	1.252 e-011	4.387 e-009	0.29	0.39
Bone(Canc ellous)	3.532 e+00	4.992 e+00	1.247 e+01	3.485 e+01	5.811 e-012	1.335 e-011	1.172 e-009	0.41	0.67
Bone (Cortical)	2.964 e+00	2.214 e+00	7.478 e+00	1.278 e+01	5.390 e-012	1.297 e-011	1.157 e-009	0.26	0.42
Brain(white matter)	5.338 e+00	3.004 e+01	2.090 e+00	7.050 e+01	7.181 e-012	2.257 e-011	1.156 e-009	0.55	0.64
Brain (grey matter)	5.830 e+00	4.216 e+01	2.754 e+00	1.371 e+02	7.187 e-012	2.246 e-011	1.399 e-009	0.56	0.62
Fat (Infiltrated)	2.994 e+00	2.467 e+00	6.066 e+00	3.139 e+01	3.970 e-012	7.904 e-012	3.736 e-009	0.09	0.14
Fat (not Infiltrated)	2.677 e+00	9.895 e-001	1.846 e+00	1.787 e+01	4.377 e-012	8.119 e-012	4.217 e-009	0.10	0.12
Heart	6.135 e+00	4.731 e+01	3.530 e+00	1.694 e+02	7.219 e-012	2.675 e-011	1.298 e-009	0.69	0.73
Kidney	6.087 e+00	4.481 e+01	4.010 e+00	1.837 e+02	7.240 e-012	3.034 e-011	1.218 e-009	0.78	0.81
Lens	5.415 e+00	3.256 e+01	8.388 e+00	3.041 e+02	6.719 e-012	1.063 e-011	3.909 e-009	0.23	0.29
Liver	5.536 e+00	3.597 e+01	3.353 e+00	1.073 e+02	7.861 e-012	2.158 e-011	1.206 e-009	0.61	0.73
Lung (Inflated)	3.237 e+00	1.690 e+01	1.096 e+00	8.641 e+01	7.199 e-012	2.353 e-011	1.802 e-009	0.57	0.60
Muscle	5.896 e+00	4.570 e+01	2.956 e+00	3.241 e+02	6.474 e-012	1.390 e-011	3.443 e-009	0.28	0.33
Skin (wet)	5.579 e+00	3.654 e+01	2.349 e+00	1.308 e+02	7.191 e-012	2.267 e-011	1.490 e-009	0.56	0.60
Skin (dry)	4.136 e+00	3.251 e+01	2.499 e+00	1.256 e+02	7.248 e-012	5.272 e-011	1.380 e-009	0.44	0.25
Spleen	6.014 e+00	4.531 e+01	3.175 e+00	2.053 e+02	7.218 e-012	2.607 e-011	1.517 e-009	0.66	0.69

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