Development Of Accurate UWB Dielectric Properties Dispersion At CST Simulation Tool For Modeling Microwave Interactions With Numerical Breast Phantoms

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ABSTRACT

In this paper, a reformulation for the recently published dielectric properties dispersion models of the breast tissues is carried out to be used by CST simulation tool. The reformulation includes tabulation of the real and imaginary parts versus frequency on ultra-wideband (UWB) for these models by MATLAB programs. The tables are imported and fitted by CST simulation tool to 2nd or 1st order general equations. The results have shown good agreement between the original and the imported data. The MATLAB programs written in MATLAB code are included in the appendix.

Index Terms— Breast cancer, dielectric properties, UWB, CST simulation tool, phantom.

1. INTRODUCTION

In worldwide, the occurrence of breast cancer has increased by 0.5% annually, with between 1.35 and 1.45 million new cases projected by 2010. Breast cancer mortality is on the decline in industrialized countries and this decline can be attributed in small part to increased breast cancer screening, and the early detection and treatment of the disease [1].

In the last decade, many researches on both diagnostic and therapeutic microwave techniques benefit from numerical breast phantoms that model structural complexities, tissue heterogeneity, and dispersive dielectric properties [2]. The one of well-known simulation tools that can be used in the investigation of these microwave techniques is CST (Computer Simulation Technology) software package which is based on the Finite-Integration Technique (FIT) [3].

In the previous published small-scale experimental dielectric spectroscopy studies, the accuracy of the assumed dielectric properties of the various tissues in the breast has been limited by gaps and disagreements. Recently, a large-scale study on normal breast tissue dielectric properties has been reported by Lazebnik et al. [4] [5] which highlighted a significant dielectric contrast between normal adipose and fibroglandular/fibroconnective tissues within the breast while the dielectric-properties contrast between malignant and normal fibroglandular tissues is no more than approximately 10. This low contrast makes the detection by microwave techniques more difficult because they depend basically on the dielectric difference between normal and malignant tissue at microwave frequencies.

2. DIELECTRIC PROPERTIES MODELS OF THE BREAST TISSUES

The Cole-Cole Model offers an efficient and accurate representation of many types of biological tissues over a very wide frequency band and has been used to reduce the complexity of the experimental data obtained for various human breast tissues (brain, fat, breast, skin, bone, etc.) [6]. The recent study by Lazebnik et al. [4] [5] has fit the wideband dielectric properties of normal/malignant breast tissue to Single-Pole Cole-Cole dispersion model, then a Single-Pole Debye models fit over the frequency band (3–10 GHz described in [2] has been generated for the above Single-Pole Cole–Cole models for lower calculation time of simulation. Table (1) and (2) show the Single-Pole Cole–Cole parameters for the nine wideband dielectric properties curves [2] [5], where the maximum corresponds to the frequency-by-frequency maximum dielectric properties (envelope) of all the curves and the minimum represents the dielectric properties of lipids [2].

| Table 1. Single-Pole Cole–Cole parameters for the eight wideband dielectric properties curves [2]. |
|---|---|---|---|---|---|---|
| n | \( \epsilon_{\infty} \) | \( \Delta \epsilon \) | \( \tau \) (ps) | \( \alpha \) | \( \sigma_e \) (S/m) |
| 1 | Maximum | 1.000 | 66.31 | 7.585 | 0.063 | 1.370 |
| 2 | Glandular-high | 6.151 | 48.26 | 10.26 | 0.049 | 0.809 |
| 3 | Glandular-median | 7.821 | 41.48 | 10.66 | 0.047 | 0.713 |
| 4 | Glandular-low | 9.941 | 26.60 | 10.90 | 0.003 | 0.462 |
| 5 | Fat-high | 4.031 | 3.654 | 14.12 | 0.055 | 0.083 |
| 6 | Fat-median | 3.140 | 1.708 | 14.65 | 0.061 | 0.036 |
| 7 | Fat-low | 2.908 | 1.200 | 16.88 | 0.069 | 0.022 |
| 8 | Minimum | 2.293 | 0.141 | 16.40 | 0.251 | 0.002 |

| Table 2. Single-Pole Cole–Cole parameters for the malignant wideband dielectric properties curves [5]. |
|---|---|---|---|---|---|---|
| n | \( \epsilon_{\infty} \) | \( \Delta \epsilon \) | \( \tau \) (ps) | \( \alpha \) | \( \sigma_e \) (S/m) |
| 9 | Malignant | 9.058 | 51.31 | 10.84 | 0.022 | 0.889 |
Table (3) shows the Single-Pole Debye parameters in the frequency range of (3–10 GHz) for the eight wideband dielectric properties curves [2].

**Table 3.** Single-Pole Debye parameters (3–10 GHz) for the eight wideband dielectric properties curves [2].

<table>
<thead>
<tr>
<th>n</th>
<th>Method</th>
<th>ε∞</th>
<th>Δε</th>
<th>τ (ps)</th>
<th>σ (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Maximum</td>
<td>23.2008</td>
<td>46.0517</td>
<td>13.00</td>
<td>1.3057</td>
</tr>
<tr>
<td>2</td>
<td>Glandular-high</td>
<td>14.2770</td>
<td>40.5152</td>
<td>13.00</td>
<td>0.6381</td>
</tr>
<tr>
<td>3</td>
<td>Glandular-median</td>
<td>13.8053</td>
<td>35.5457</td>
<td>13.00</td>
<td>0.7384</td>
</tr>
<tr>
<td>4</td>
<td>Glandular-low</td>
<td>12.8485</td>
<td>24.6430</td>
<td>13.00</td>
<td>0.2514</td>
</tr>
<tr>
<td>5</td>
<td>Fat-high</td>
<td>3.9870</td>
<td>3.5448</td>
<td>13.00</td>
<td>0.0803</td>
</tr>
<tr>
<td>6</td>
<td>Fat-median</td>
<td>3.1161</td>
<td>1.5916</td>
<td>13.00</td>
<td>0.0496</td>
</tr>
<tr>
<td>7</td>
<td>Fat-low</td>
<td>2.8480</td>
<td>1.1041</td>
<td>13.00</td>
<td>0.0214</td>
</tr>
<tr>
<td>8</td>
<td>Minimum</td>
<td>2.3086</td>
<td>0.0918</td>
<td>13.00</td>
<td>0.0048</td>
</tr>
</tbody>
</table>

3. REFORMULATION

In CST simulation tool, none of the above models exist (except Debye model without including the conductivity), a Debye model fit in [7] was used for the above Single-Pole Debye parameters with ignoring the conductivity. The conductivity term in the model is necessary in order to model accurately the low-frequency behavior of the imaginary part of the relative dielectric permittivity. Without the conductivity term, the Debye model forces the imaginary part of the dielectric constant to zero at zero frequency [8], and that is clearly not the case given in Table (3). To use CST in breast cancer phantoms simulation, the two above models could be reformulated for UWB usage in CST simulation tool.

In CST simulation tool a more general approach for defining the dielectric properties of any material on a very wideband frequency ranges include the definition of both $\varepsilon'_r$ and $\varepsilon''_r$ on frequency bandwidth and then fitting these two models to a general first or second order equation defined as:

$$\varepsilon_r(\omega) = \varepsilon_\infty + \frac{\Delta \varepsilon}{1 + (j\omega\tau_0)^{1-a}} + \frac{\sigma}{j\omega\varepsilon_0}$$  \hspace{1cm} (3)

where $\Delta \varepsilon = \varepsilon_x - \varepsilon_\infty$

To find $\varepsilon'_r$ and $\varepsilon''_r$ from Single-Pole Cole–Cole parameters, the following formula [10] is used:

$$\varepsilon_r(\omega) = \varepsilon_\infty + \frac{\Delta \varepsilon}{1 + (j\omega\tau_0)^{1-a}} + \frac{1}{(j\omega\tau)^r}$$  \hspace{1cm} (4)

The real and imaginary parts of Eq. (3) are [7]:

$$\varepsilon'_r(\omega) = \varepsilon_\infty + \left[1 - \frac{\sin(\beta ln \omega \tau_0)}{\cos(\beta ln \omega \tau_0) + \cos \frac{\beta \pi}{2}}\right] \times \frac{\Delta \varepsilon}{2} + (\cosh(\gamma ln \omega \tau) - \sinh(\gamma ln \omega \tau)) \times \cosh \frac{\gamma \pi}{2}$$  \hspace{1cm} (5)

$$\varepsilon''_r(\omega) = \frac{\sin \frac{\beta \pi}{2}}{\cosh(\beta ln \omega \tau) + \cos \frac{\beta \pi}{2}} \times \frac{\Delta \varepsilon}{2} + (\cosh(\gamma ln \omega \tau) - \sinh(\gamma ln \omega \tau)) \times \sin \frac{\gamma \pi}{2}$$  \hspace{1cm} (6)

where $\tau$ and $\tau_0$ are the relaxation time constants; $\beta$ and $\gamma$ represent the degree of relaxation distribution. Equation (4) includes two relaxation time constants without including the conductivity term, while the Single-Pole Cole–Cole given in Eq.(3) includes one relaxation time constant with the conductivity term included, the corresponding parameters of Eq. (3) relative to Eq.(4) are given in Table (4).

**Table 4.** The corresponding parameters of Eq. (3) relative to Eq.(4)

<table>
<thead>
<tr>
<th>Eq. (3)</th>
<th>Eq. (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$</td>
<td>$\tau_0$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>$\tau$</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>$\gamma$</td>
</tr>
</tbody>
</table>

From Table (4), the following could be concluded. The third term in Eq.(5) will be canceled while the second term of Eq.(6) is will be $\sigma/\omega\varepsilon_0$ . therefore, $\varepsilon'_r$ and $\varepsilon''_r$ given in Eq. (3) are:

$$\varepsilon'_r(\omega) = \varepsilon_\infty + \left[1 - \frac{\sin(\beta ln \omega \tau_0)}{\cos(\beta ln \omega \tau_0) + \cos \frac{\beta \pi}{2}}\right] \times \frac{\Delta \varepsilon}{2}$$  \hspace{1cm} (9)

$$\varepsilon''_r(\omega) = \frac{\sin \frac{\beta \pi}{2}}{\cosh(\beta ln \omega \tau) + \cos \frac{\beta \pi}{2}} \times \frac{\Delta \varepsilon}{2} + \frac{\sigma}{\omega\varepsilon_0}$$  \hspace{1cm} (10)

where $\beta = 1 - a$
4. PROGRAMMING

A MATLAB program (I) is written to use the data given in Tables (1) and (2) with the Eqs. (9) and (10) to tabulate \( \varepsilon'_r \) and \( \varepsilon''_r \) at different frequencies. The results are put in a text file in a table form versus frequency. The value of \( n \) in Tables (1) and (2) determines the tissue type in the program. For each value of \( n \), print the name of tissue in the brackets of "fopen()" and at "type" instructions as well.

At CST simulation tool, for each material: choose "user" from dispersion window "Dispersion list", then load file and choose "General 2nd". Figure (1) shows the real and imaginary parts of the original curves ("list" in the figure) and their 2nd order fitting curves in CST simulation tool. All curves are in

Figure 1. The real and imaginary parts of the relative permittivity of the original curves ("list" in the figure) and their 2nd order fitting curves in CST simulation tool.
good agreement with the original curves from 1.25GHz to 20GHz
For obtaining 1st order fitting curve, we will choose "General 1st" order fitting for the imported Single-Pole Cole–Cole at CST simulation tool, but we will run MATLAB program in the same band used (here 3–10 GHz) for most curves and importing them in the same band at CST simulation tool to have good accuracy. Also, the Single-Pole Debye parameters (3–10 GHz) can be used to import the curves. Single-Pole Debye equation is expressed as [12]:

\[ \varepsilon_r = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau} + \frac{\sigma}{\omega\varepsilon_0} \]  \hspace{1cm} (11)

and its real and imaginary parts are:

\[ \varepsilon'_r = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \omega^2\tau^2} \]  \hspace{1cm} (12)

\[ \varepsilon''_r = \frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{1 + \omega^2\tau^2} + \frac{\sigma}{\omega\varepsilon_0} \]  \hspace{1cm} (13)

Another MATLAB program (II) is written which uses Eqs. (12) and (13) besides Table (3) to form a table of \(\varepsilon'_r\) and \(\varepsilon''_r\) at different frequencies and put the results in a text file. At CST simulation tool, the "General 1st" should be chosen at loading the file. The MATLAB program is to be run in the same band of use (here 3-10GHz) at CST simulation tool for good accuracy. Figure (2) shows the 1st order fitting curves of glandular-high tissue of Single-Pole Cole–Cole and Single-Pole Debye curves, respectively. For comparison, the 1st order curves result of the two models don't approximately different for most curves except the imaginary part of fat-low that don't have accurate curve from the original data and its fitting curves are inaccurate for real and imaginary part.

The dielectric properties of skin and muscle are well known in the microwave frequency range, and can be selected from reliable databases [2], such as that provided by Gabriel et al. [13] and assigned to the skin and chest wall regions of the phantoms in a straightforward manner [2]. For CST simulation tool, only \(\varepsilon'_r\) and \(\varepsilon''_r\) will be needed from the tables of reference [13]; therefore, any table will be copied to a text file and \(\varepsilon'_r\) and \(\varepsilon''_r\) will be imported by MATLAB, then MATLAB program (III) is written to print them to a text file. However, for the frequencies under 0.993GHz the skin table in reference [13] has miss fitting to a general second order equation Eq. (2) in CST simulation tool; therefore, the data will be deleted before this range at MATLAB. Figure (3) show the original curves of the permittivity of skin and their fitting curves at CST simulation tool.

The programs (I) - (III) written in MATLAB code are included in the appendix.

5. CONCLUSION

In this work, we explain how to convert and simulate the dielectric properties dispersion of the breast tissues in
CST simulation tool that is widely used. Also, this work explains how to convert and simulate in CST simulation tool the dielectric properties dispersion of other tissues and materials that have Single-Pole Cole-Cole, Single-Pole Debye dispersion or any order or dispersion type by simple exchange of $\varepsilon'_r$ and $\varepsilon''_r$ relations in the programs below and their parameters matrices for the given dispersion formula.

6. REFERENCES


APPENDIX

PROGRAM (I)

```matlab
% Program (I) uses the two equations (8) and (9) with tables(2)and(3)to ...
%form a table of the real and imaginary parts of the relative permittivity ...
%at different frequencies and put the results in a text file.
% Frequency f in GHz
% tao in ps

clear
sema=[1.370;0.809;0.713;0.462;0.083;0.036;0.020;0.002;0.889];
epsinf=[1.6151;7.821;9.941;4.031;3.140;2.908;2.293;9.058];
deltaeps=[66.310;48.260;41.480;26.600;3.654;1.708;1.200;0.141;51.310];
alfa=[0.063;0.049;0.047;0.003;0.055;0.061;0.069;0.251;0.022];
n=7;

fid = fopen('fat-low.txt','w');
t=0;
for f=0.5:0.125:20;
t=t+1;
REPS(t)=epsinf(n)+(1-sinh((1-alfa(n))*log(2*pi*f*10^9*tao(n)*10^-12))/...
\[
\begin{align*}
\cos((1-\alpha(n)) \pi/2)) \times \delta\epsilon(n)/2; \\
\text{IMEPS}(t) &= \sin((1-\alpha(n)) \pi/2)/ \\
&\times \cosh((1-\alpha(n)) \log(2\pi f \times 10^9 \tau(n) \times 10^{-12}))+... \\
&\times \cos((1-\alpha(n)) \pi/2)) \times \delta\epsilon(n)/2+\sigma(n)/(2\pi f \times 10^9 \times 8.854 \times 10^{-12}); \\
&\text{fprintf(fid, } '%f %f %f
', f, \text{REPS}(t), \text{IMEPS}(t)); \\
&\text{fclose(fid);} \\
&\text{view the contents of the file}
\end{align*}
\]

PROGRAM (II)

% Program (II) uses the two equations (11) and (12) with table(3) to
...form a table of the real and imaginary parts of the relative permittivity
...at different frequencies and put the results in a text file.
% Frequency f in GHz
% \tau in ps
clear
sigma=[1.3057; 0.6381; 0.7384; 0.2514; 0.0803; 0.0496; 0.2514; 0.0048];
tau=[13.00; 13.00; 13.00; 13.00; 13.00; 13.00; 13.00; 13.00];
epsilon=[23.2008; 14.2770; 13.8053; 12.8485; 3.9870; 3.1161; 2.8480; 2.3086];
deltaepsilon=[46.0517; 40.5152; 35.5457; 24.6430; 3.5448; 1.5916; 1.1041; 0.0918];
n=7;
    fid = fopen('fat-low.txt', 'w');
t=0;
    for f=3:0.125:10;
    t=t+1;
    \text{REPS}(t) = \epsilon(n) + \delta\epsilon(n)/(1+(2\pi f \times 10^9 \times \tau(n) \times 10^{-12})^2);
    \text{IMEPS}(t) = \delta\epsilon(n)/(1+(2\pi f \times 10^9 \times \tau(n) \times 10^{-12})^2)\times...
    (2\pi f \times 10^9 \times \tau(n) \times 10^{-12})+\sigma(n)/(2\pi f \times 10^9 \times 8.854 \times 10^{-12});
    fprintf(fid, '%f %f %f
', f, \text{REPS}(t), \text{IMEPS}(t)); \\
    fclose(fid);
% view the contents of the file

PROGRAM (III)

% Program (III) for re-tabling of Gabriel tables.
    fid = fopen('dry-skin.txt', 'w');
t=0;
    for t=127:156;
    fprintf(fid, '%f %f %f
', data(t,1)/10^9, data(t,2), data(t,3));
    fclose(fid);
% view the contents of the file

% type dry-skin.txt