Dielectric Property Measurement of Skin and Dosimetry for Millimeter Wave Irradiation up to 100 GHz

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Abstract—Several wireless communication technologies operating in the millimeter wave (MMW) band are already in practical use. Therefore, a safety analysis of exposure to MMW frequency is required. In this study, we measured dielectric properties of epidermis and dermis at up to 110 GHz using enucleated porcine skin, because of measurement data scarcity for biological tissues in the MMW band. The Measurement results were compared with literature values. Furthermore, a numerical dosimetry study was conducted using a 2D forearm model, and localized energy absorption inside the forearm was evaluated. The frequency dependence of energy absorption obtained from the dielectric property measurements is compared with that obtained from literature.

I. INTRODUCTION

Recently, wireless communication technologies operating in the millimeter wave (MMW) band, such as very-high-speed wireless communication systems, high spatial resolution radar, and security systems, have become increasingly common. With increasing public exposure to MMWs, evaluating the health effects of exposure to MMWs has become an important issue. MMWs absorbed by the body surface raises tissue temperature; this phenomenon is considered as the dominant biological effect of MMW exposure. International safety guidelines [1]-[2] use the incident power density of MMWs as their basic restrictions. However, the values for the human safety limit in the MMW band have been determined by interpolating between experimental results at the microwave and IR frequency regions. Therefore, direct assessment of the safety analysis in the MMW band is important to determine the appropriateness of the basic guidelines.

We are now planning the dosimetry of energy absorption inside the body by using numerical simulations in the MMW band. While several dosimetry studies have been reported [3]-[9], the dielectric properties used in these dosimetry studies are extrapolated from measurement data below the MMW frequency region. Thus, measurement data of dielectric properties for biological tissues are prerequisite for precise dosimetry.

In this study, we focused on energy absorption inside the skin tissue. Because of the depth of penetration at MMW frequencies, skin effects of MMW irradiation are a priority issue. Dielectric property measurements of the skin were performed at up to 110 GHz. The results were compared with literature values and used to develop a parametric model. Furthermore, dosimetry was performed on a human forearm to assess energy absorption due to MMW irradiation. Energy absorption values using our dielectric properties were compared with those obtained using literature values.

II. MEASUREMENT OF DIELECTRIC PROPERTIES

A. Biological Tissues

Skin is composed of epidermis, dermis, and subcutaneous tissues. The thickness of the epidermis and dermis is approximately 0.2 mm and 2 mm respectively for a human forearm. Epidermis can be further separated into several sublayers, with the outermost sublayer being the stratum corneum. Previously, dielectric properties of the stratum corneum and epidermis were estimated using measurement data from in vivo experiments; however, dielectric properties which obtained from directly measurement of the tissues are also necessary for validation.

In this study, enucleated porcine skin was precisely fractioned into epidermis and dermis. Measurements were performed up to 48 hours after the animal was sacrificed.

B. Experimental Setup

Three measurement systems were used for the measurement of dielectric properties from 10 MHz to 110 GHz. Commercial measurement systems employing the dielectric probe method were used from 10 MHz to 500 MHz (DAK-12, Schmid & Partner Engineering AG) and from 500 MHz to 50 GHz (85070E, Agilent Technologies). Each dielectric probe was connected to a vector network analyzer (E8364B or E8364C, Agilent Technologies).

The free-space method with spot-focus-type lens antennas was used for dielectric property measurements from 50 to 110 GHz [10]. A pair of lens antennas (KLA-002, Kanto Electronic Application and Development Inc.) was connected to a vector network analyzer (E8361A, Agilent Technologies) via MMW frequency extender (N5260A, Agilent Technologies).

Dielectric property measurements for the epidermis and dermis were performed at 37 °C from 10 MHz to 110 GHz. Water bath units (MAT-S-OTOR-MJ, Tokai Hit) and localized air conditioners (PAU-AZ1800SE, Apiste) were used to control the temperature of biological tissues used in the dielectric probe and free-space methods, respectively.
Measurement results were used to develop parametric models. Here, the double Cole-Cole model, shown in Eq. (1), was employed.

\[
\varepsilon(f) = \varepsilon_{\infty} + \sum_{l=1}^{2} \frac{\Delta_{l}}{1 + (f/f_{r,l})^{(1-\alpha_{l})}} - \frac{\sigma_{s}}{j2\pi f\varepsilon_{0}}
\]

where \(\varepsilon_{\infty}\) and \(\sigma_{s}\) are the permittivity limit at infinity and the DC conductivity of the samples, respectively, and \(f_{r,l}\) and \(\alpha_{l}\) are the relaxation frequency and the distribution parameter.

Each parameter of the parametric models was determined by solving the least-squares problem by the Levenberg-Marquardt method.

C. Results of Dielectric Property Measurement

Cole-Cole parameters for the epidermis and dermis are listed in Table I. The relaxation frequency for \(\gamma\) dispersion, which corresponds to dielectric dispersion of a water molecule, is \(f_{r,1}\) in the table. According to Ellison’s parametric model, the relaxation frequency of pure water at 37 \(^{\circ}\)C is approximately 25 GHz [11]. The relaxation frequency of \(\gamma\) dispersion for pure water fairly agreed with those of both epidermis and dermis.

Water content of the epidermis and the dermis, measured by a halogen moisture analyzer (HB43-S, Mettler Toledo), was 9.5\% ± 0.5\% and 65\% ± 5\%, respectively. Large differences exist in the water content in each epidermis and dermis, however, both relaxation frequencies of the \(\gamma\) dispersion agree with that of pure water. Thus, it is suggested that relaxation frequency of the \(\gamma\) dispersion for skin layers agrees with that of pure water and is independent of the water content.

<table>
<thead>
<tr>
<th>Tissue</th>
<th>(\varepsilon_{\infty})</th>
<th>(\sigma_{s}) [S/m]</th>
<th>(f_{r,1}) [GHz]</th>
<th>(\Delta_{1})</th>
<th>(\alpha_{1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epidermis</td>
<td>2.12</td>
<td>0.327</td>
<td>27.0</td>
<td>27.9</td>
<td>0.109</td>
</tr>
<tr>
<td>Dermis</td>
<td>2.85</td>
<td>0.447</td>
<td>24.1</td>
<td>35.1</td>
<td>0.126</td>
</tr>
</tbody>
</table>

\(f_{r,2}\) [MHz] \(\Delta_{2}\) \(\alpha_{2}\)
89.8 19.1 0.288
646 12.7 -0.020

Figure 1 shows the dielectric properties obtained from the parametric models developed from our measurement results. Vertical axes of the graph denote real and imaginary parts of the relative complex permittivity, and horizontal axes denote the frequency up to 1 THz. Dielectric properties from literature are also shown. The results indicate that dielectric properties of the dermis exceed those of the epidermis up to 110 GHz. These results are due to the difference in water content; \(\gamma\) dispersion is expected to be dominant in this frequency region.

Dielectric properties of the epidermis and dermis were compared with literature values [12]-[14] in Fig. 1. Table II summarizes the conditions for the dielectric measurements for all data shown in Fig. 1. Our measurement data were obtained from enucleated skin on porcine at 37 \(^{\circ}\)C, whereas the literature values were obtained from \(in\) \(vivo\) experiments on humans. Therefore, the results obtained from our parametric model include uncertainty terms due to animal species, freshness, and temperature.

Deviations in the real and imaginary parts of the relative complex permittivity (\(\Delta\varepsilon_r\), \(\Delta\varepsilon_i\)) between literature values and our results are shown below. The values of deviations of dry skin measured by Gabriel [12] [13] from our dermis result are \(\Delta\varepsilon_r \leq 1.0\) and \(\Delta\varepsilon_i \leq 1.7\) up to 20 GHz. These results indicate good agreement. Thickness of epidermis was relatively thinner than penetration depth up to 20 GHz. Therefore, dielectric property for dermis is considered dominant for the \(in\) \(vivo\) experiments performed by Gabriel.

Deviations in the relative complex permittivity of epidermis between Pickwell’s report [14] and our measurement results are \(\Delta\varepsilon_r \leq 0.5\) and \(\Delta\varepsilon_i \leq 1.8\) from 100 GHz to 110 GHz. These deviations are similar order to the deviations for the dermis show above. Our result agreed well with data measured at the terahertz frequency region. Thus, the dielectric properties obtained through our experiments have been validated.

<table>
<thead>
<tr>
<th>Study</th>
<th>Frequency</th>
<th>Method</th>
<th>Material</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>This</td>
<td>500 MHz -110 GHz</td>
<td>Coaxial Probe &amp; Free Space Method</td>
<td>Epidermis &amp; Dermis (Porcine)</td>
<td>Enucleated Porcine Skin @ 37 (^{\circ})C</td>
</tr>
<tr>
<td>Gabriel 1996 [13]</td>
<td>150 MHz -20 GHz</td>
<td>Coaxial Probe</td>
<td>Dry Skin (Human)</td>
<td>(in) (vivo)</td>
</tr>
<tr>
<td>Pickwell 2004 [14]</td>
<td>100 GHz -3 THz</td>
<td>THz-TDS</td>
<td>Epidermis (Human)</td>
<td>(in) (vivo)</td>
</tr>
</tbody>
</table>
III. DOSIMETRY FOR ENERGY ABSORPTION

Electromagnetic field analysis inside the body was performed using the dielectric properties obtained in the previous section. Specific absorption rate (SAR) inside the forearm model was assessed at several MMW frequencies. SAR is defined as Eq. (2).

$$\text{SAR} = \frac{\sigma |E|^2}{2\rho}$$

(2)

where, \(\sigma\), \(|E|\), and \(\rho\) are conductivity, amplitude of electric field, and density, respectively.

A. Condition for EMF Analysis

The finite difference time-domain (FDTD) method [15] was used to analyze SAR. The two-dimensional forearm model was employed. Energy absorption by plane wave injection toward the +x direction (see Fig. 2) was used as the wave source. Incident power density of the plane wave was set as 1 mW/cm². Figure 2 is the 2D forearm model used in the dosimetry; this simulation model was obtained as follows. The forearm of a male Japanese model (Taro) [16] was reconstructed to a 0.125 mm resolution model, and the skin region was separated into epidermis and dermis. Thickness of the epidermis was fixed at 0.25 mm (2 voxels) over the skin’s surface, and the rest of the skin voxel was treated as dermis.

Dielectric properties for the epidermis and dermis were set from the Cole-Cole model described in Eq. (1) and Table I. Properties of the five other tissues were estimated from Gabriel’s Cole-Cole models [12] [17]. The database of biological tissue densities reported in [18] was used to calculate SAR.

B. Results of EMF Analysis

Figure 3 shows the distribution of SAR at 40, 60, 76, and 94 GHz. SAR distributions in the figures were normalized with the maximum value of SAR for each frequency. The figure shows that SAR penetration depth gradually decreased with increasing frequency. Energy absorbed inside the epidermis and the dermis agrees to the total energy absorbed inside the forearm with no larger than 0.05 dB deviation. It indicates that almost energy injected inside the forearm was absorbed in the epidermis and the dermis.

Dependence of the maximum value of spacial-averaged SAR to the average volume is shown in Fig. 4. If averaging volume include air region, such as surface of the forearm, the value of spacial-averaged SAR is not used due to the IEEE recommendation of the spacial-average SAR calculation inside the body [20]. Vertical and horizontal axes are maximum value of spacial-averaged SAR and length of the averaging cubic volume, respectively. The spacial-average SARs were normalized with voxel peak SAR at 95 GHz in the figure. In the basic safety guidelines for EMF irradiation, mass-averaged SAR (1 g or 10 g averaged SARs) is used to assess the localized exposure in the microwave frequency band [1].
this is because mass-averaged SAR values show good relationship with temperature rise up to 6 GHz [19].

Figure 4 indicates that the value of voxel peak SAR increased with increasing of frequency. While, the maximum value of spacial-averaged SAR agreed between each frequency with no larger than 0.5 dB deviation when averaging volume was larger than 1 mm cubic volume.

Next, the values of SAR were compared with those obtained using Gabriel’s skin dielectric properties. Here, dielectric properties of both epidermis and dermis were replaced with dry skin reported by Gabriel [12] from the forearm model. The values of energy absorption inside the forearm were agreed with no larger than 0.2 dB deviations. While the voxel-peak SAR from Gabriel’s skin became approximately 0.6 dB greater than the result from our dielectric properties at 40 GHz, the spacial-averaged SAR agreed with 0.2 dB deviation when averaging volume was larger than 0.5 mm cubic volume.

IV. Conclusion

In this study, dielectric property measurements of epidermis and dermis were performed at up to 110 GHz at a tissue temperature of 37 °C. Emuciated porcine skin was used for the measurement. The parametric models for both epidermis and dermis were developed using double Cole-Cole models. The relaxation frequency of γ dispersion agreed well with that of pure water. The dielectric properties of dermis were greater than those of epidermis because of the differences in water content in each skin layer. Our dielectric properties were compared with the literature values obtained from in vitro human experiments. The dielectric properties for dermis agreed well with literature values, which were reported up to 20 GHz. The values for epidermis also agreed well with literature values, which were reported up to over 100 GHz. Thus, our measurement results have been validated.

Energy absorption inside the forearm was assessed at several MMW frequencies. The result indicated that almost all energy injected inside the forearm is absorbed at the skin layers. The maximum values of spacial-averaged SAR were also assessed as preliminary work. The value of the voxel-peak SAR increased with increasing of the frequency. While, the value of spacial-averaged SAR agreed with no larger than 0.5 dB deviation for each frequency when averaging volume was larger than 1 mm cubic volume. Finally, the values of SAR from our dielectric measurement were compared with those calculated from literature. The result indicated that spacial-averaged SAR agreed with 0.2 dB deviations when averaging volume was larger than 0.5 mm cubic volume.

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REFERENCES


