1. Introduction

Much work has been done to demonstrate electrical properties in biomaterials over a wide frequency range. Among the properties, the permittivity of biological tissues is studied for decades. The permittivity of a material is a function of numerous factors including its constituent materials. The biological tissue is a heterogeneous material and mainly consists of water. It is known that the complex permittivity in gigahertz region stands for the water content in the material.[1] But the state of the water can vary according to how electrochemically bound it is to surrounding biomaterial such as cells and proteins.

One of the objectives of this paper is to show that the wideband permittivity measurement of biological tissue can be used to investigate the state of it. The dehydration of biological tissue is greatly depended on the exposure time to the air. To prove the relations of the permittivity and the water concentration change in biological material, dehydrating by sulfuric acid in vacuum desiccator is performed. The permittivity of a biological material is measured as it is dehydrated. Apple and pork (muscle and fat) tissues are selected considering the characteristics of biological materials.

The other objective is to suggest permittivity measuring and calibrating method of using open ended coaxial antenna. It can be used as a sensor for non-destructive dielectric measurements over a broad frequency band. Reflection coefficient measurement by calibrated coaxial antenna from 45MHz to 67GHz can show reliable permittivity of measured biological tissues. But to extract precise permittivity value, the calibration material should be carefully selected.

2. Coaxial Antenna Measurement Setup

The reflection coefficient measurement with open-ended coaxial antenna as a sensor is widely used. The vector network analyzer, including the test cable in fig. 1, can be calibrated for
one-port measurements using calibration kit (open, short and 50 ohm load). But the open ended coaxial antenna after the test cable is hard to be calibrated by short and load condition up to 67 GHz. So, permittivity known material is used for calibration standard. The complex permittivity is derived from the measured reflection coefficients using (1).

\[
\frac{(\varepsilon_m - \varepsilon_A)(\varepsilon_B - \varepsilon_C)}{(\varepsilon_m - \varepsilon_B)(\varepsilon_C - \varepsilon_A)} = \frac{(\Gamma_m - \Gamma_A)(\Gamma_B - \Gamma_C)}{(\Gamma_m - \Gamma_B)(\Gamma_C - \Gamma_A)}
\]

(1)

Where \(\varepsilon_i\) represents the complex permittivities of the calibration materials (i = A, B, C) and the measured sample (i = m), and \(\Gamma_i\) represents the reflection coefficient at the measurement plane. After calibration, the capacitance model in fig. 2 is used to determine the complex permittivity of the sample contacting the coaxial aperture from measurements of the reflection coefficient. The complex permittivity consists of a real part and an imaginary part as shown (2).

\[
\hat{\varepsilon} = \varepsilon' - j\varepsilon''
\]

(2)

Where \(\varepsilon'\) refers to the real part of the complex permittivity and represents the amount of polarization by externally applied electromagnetic fields, while the imaginary part of the complex permittivity represents the energy loss per period.

Figure 2: Capacitance model of coaxial antenna

The measurement setup was calibrated by using air, distilled water and methanol at frequencies from 2 GHz to 67 GHz. While air, short in mercury and saline (0.9 %) is used over the frequency range 45 MHz to 2 GHz. Similar reflection coefficients of calibration materials can cause the discrepancy to the right side of (1). So distilled water, methanol and air cannot be used at once for low frequency calibration. For the same reason, the permittivity differences of calibration materials should be large enough to guarantee the left side the equation. The complex permittivities of reference materials are shown in fig. 3.

Figure 3: Complex permittivity of calibration material (a) real (b) image
3. Experiment

For the experiment, apple and pork (muscle and fat) tissues are selected. The presence of a cell wall distinguishes plant cell from animal cell. An apple tissue has a rigid wall surrounding the plasma membrane. We can assume that the pork tissues would dehydrate more completely and faster than the apple tissues. To dehydrate the samples without contamination, a desiccator in fig. 4 was used. The desiccator is a sealable enclosure containing desiccants normally used to keep the samples from humidity. It can also be applicable to dry the samples with the aid of sulfuric acid. Concentrated sulfuric acid is a power desiccant that it will absorb moisture from the air and will even dehydrate other materials in order to absorb the water. Alcohol and salt are also desiccants, but they change the characteristics of dehydrated materials.

![Desiccator](image)

Figure 4: A desiccator to dehydrate the measured samples

1.1 mm outer diameter semi-rigid type coaxial antenna (11 cm length) was used for the test. It maintains 50 ohm characteristic impedance up to 110 GHz.[2] A portable network analyzer (E8361A) was set up for one-port measurement with -15dBm port power. The samples were removed from the desiccator at 3 hour intervals for the permittivity measuring and weighing. The test was conducted until constant weight was attained.

4. Results

As the sample was dehydrated, the measured real permittivity value in fig. 5 also decreased and the center frequency of the peak image value shifted to lower side. Even though the pork muscle and the apple have similar water contents (76 %), the patterns of complex permittivity are quite different. While the weight of pork muscle steadily diminished, the apple showed smaller change(7 %) until 6 hour. Pork fat showed 5 % weight change and lower real permittivity value than other tissues.

![Complex permittivity](image)

Figure 5: Complex permittivity of (a) pork muscle and (c) apple
For more detailed analysis, parameter value was extracted from Cole-Cole equation.[3] The measured data was fitted to (3) which includes two relaxation times.

\[
\varepsilon = \varepsilon_\infty + \frac{\Delta \varepsilon_1}{1 + (j \omega / f_{c1})^{1-\alpha_1}} + \frac{\Delta \varepsilon_2}{1 + (j \omega / f_{c2})^{1-\alpha_2}} - j \frac{\sigma}{2 \pi \varepsilon_0}
\] (3)

Above equation, \(\varepsilon_\infty\) is extrapolated real permittivity at significantly higher frequencies than the relaxation frequency \(f_{c1}\). \(f_{c1}\) is mainly related to dispersions of protein or cell membrane in megahertz region. \(f_{c2}\) is to dispersion of water. \(\alpha\) represents purity of the material. \(\Delta \varepsilon\) means difference between \(\varepsilon_\infty\) and extrapolated lower frequency real permittivity.

Table 1 shows Cole-Cole parameters of the measured samples. The apple shows clearly two dispersions within the measured frequency range. \(\Delta \varepsilon_2\) of it is quite large until 24 hour. The dispersion frequency of \(f_{c2}\) (apple and pork muscle) decreased as time elapsed. But the change ratio is small until 50 % weight was lost. It means that 50 % of apple and pork muscle tissues are free water. It is noticeable there exists relaxation frequency of water around 5 GHz even the samples are fully dehydrated.

5. Conclusion

In this research, we measured permittivity changes as the samples were dehydrated. To extract more precise complex permittivity of measured samples, the antenna was calibrated with different permittivity known materials according to measured frequency region. Compared to pork tissue, cell wall structure of the apple shows discriminated characteristics to the permittivity as it is dehydrated. Parametric analysis by Cole-Cole equation can be utilized to check the state of the biological tissues.

Table 1: Cole-Cole parameter of the apple and pork tissues as they are dehydrated

<table>
<thead>
<tr>
<th>Sample</th>
<th>Time elapse</th>
<th>(\Delta \varepsilon_1)</th>
<th>(\alpha_1)</th>
<th>(f_{c1}) (MHz)</th>
<th>(\Delta \varepsilon_2)</th>
<th>(\alpha_2)</th>
<th>(f_{c2}) (GHz)</th>
<th>(\sigma) (S/m)</th>
<th>(\varepsilon_\infty)</th>
<th>Weight</th>
</tr>
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<tbody>
<tr>
<td>Apple</td>
<td>Initial</td>
<td>22.1</td>
<td>0.334</td>
<td>240.7</td>
<td>52.8</td>
<td>0.027</td>
<td>13.7</td>
<td>0.249</td>
<td>6.27</td>
<td>1</td>
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<tr>
<td>Apple</td>
<td>12 hour</td>
<td>24.2</td>
<td>0.323</td>
<td>316.6</td>
<td>49.0</td>
<td>0.016</td>
<td>13.1</td>
<td>0.214</td>
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<td>0.369</td>
<td>768.6</td>
<td>30.4</td>
<td>0.040</td>
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<td>0.237</td>
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<td>7.09</td>
<td>0.001</td>
<td>267.0</td>
<td>3.90</td>
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<td>0.583</td>
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<td>30.9</td>
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References