Improvement in the Electrical Characteristics of a High-hydrous Gel Phantom by the Addition of Inductive Materials at a Low-frequency Band

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Phantoms that imitate the electrical properties of a living body are widely used for various examinations. This paper reports an improvement in the electrical characteristics of a high-hydrous gel phantom by the addition of carbon microcoils and carbon fiber at a low-frequency band. This improvement occurred because the CMC and carbon fiber functioned as an inductance inside the high-hydrous phantom at a low-frequency band. The relative permittivity of a phantom with 2 wt% added carbon fiber was in good agreement with that of human muscle in a frequency range of 5 to 30 MHz.

Keywords: high-hydrous gel phantom, carbon fiber, carbon microcoils, relative permittivity, inductance.

1. Introduction

Phantoms that imitate the electrical properties of a living body are widely used in investigations of implantable[1] or wearable[2] medical electronic equipment as substitutes for animal experiments. Phantoms are actively studied in various research institutions, and various phantoms have been developed, including liquid[3], dry[4]-[6], and high-hydrous gel[7],[8] phantoms. A high-hydrous phantom, which consists mainly of deionized water, is easy to operate orthopedically while retaining the desired form, and it can imitate the broadband electrical properties of a living body. For this reason, it is a useful phantom for many applications. This article discusses the improvement of relative permittivity and conductivity of a high-hydrous phantom, which are in agreement with the electrical properties of human muscle tissue in the frequency band above 300 MHz reported in the literature at a low-frequency band. The electrical properties in the frequency band below 300 MHz, however, have not been fully investigated. According to our evaluation results[9]-[11], the phantom does not mimic the electrical properties of a living body below 30 MHz. In particular, the relative permittivity is lower than that in a living body. In addition, it was revealed that the characteristic cannot be imitated simply by adjusting the compounding ratio of materials in a conventional phantom, as shown in Table 1[8]. On the other hand, although phantoms are applied in a body area network (BAN), in some BAN studies, a phantom that can be used at a frequency of 10 MHz is needed[12]. We previously reported that the relative permittivity of a high-hydrous phantom was improved by the addition of a carbon microcoil (CMC)[13]-[15], which is carbon fiber of the micrometer order in a coil shape[16],[17]. However, the mechanism for the improvement in the electrical property by the addition of CMC was not clear. The mechanism has to be clarified to further improve the function of the phantom by the addition of carbon materials. This paper reports the electrical property of a phantom to which various carbon materials were added to clarify the mechanism.

2. Measurement methodology at a low-frequency band

The electrical properties were measured using the common electric capacity method based on the principle of a parallel-plate capacitor. Circular copper plates with a diameter of 5 cm were adopted for the electrodes in this study. The relative permittivity and conductivity were calculated using Eqs. (1) and (2), respectively.

\[
\varepsilon' = \frac{Cd}{\varepsilon_0 S} \tag{1}
\]

\[
\sigma = \frac{Gd}{S} \tag{2}
\]

where C and G are the capacitance and conductance measured using an impedance analyzer (Agilent Technology, 4294A, California, USA); d, S, and \(\varepsilon_0\) are the

<table>
<thead>
<tr>
<th>Materials</th>
<th>Weight [g]</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purified water</td>
<td>3375</td>
<td>Main material</td>
</tr>
<tr>
<td>Polyethylene powder</td>
<td>337.5</td>
<td>Relative permittivity</td>
</tr>
<tr>
<td>NaCl</td>
<td>19.6</td>
<td>Conductivity</td>
</tr>
<tr>
<td>Agar</td>
<td>104.6</td>
<td>Forming</td>
</tr>
<tr>
<td>TX−151</td>
<td>82.93</td>
<td>Thickener</td>
</tr>
<tr>
<td>Sodium dehydroacetate monohydrate</td>
<td>2.0</td>
<td>Antiseptic</td>
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</tbody>
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distance between the parallel plates, electrode area, and permittivity of vacuum ($8.854 \times 10^{-12} \text{ F/m}$), respectively. Figure 1 shows the measurement test fixture for the low-frequency band. The fixture consisted of two circular copper plates (50 mm in diameter). In order to prevent misalignment between the metal plates, a PTFE guide was employed.

3. Increasing relative permittivity by adding carbon materials

This paper deals with the electrical properties of the muscle in a living body. The relative permittivity of the conventional phantom is lower than that of the muscle in a living body. Therefore, the relative permittivity of the phantom must be increased. Increasing capacitance $C$ causes the relative permittivity to increase, as shown in Eq. (1). If an inductance is inserted in series with $C$, the effective capacitance increases, and therefore the effective relative permittivities increase, as shown in Fig. 2 and Eq. (3).

$$C^* = \frac{C}{1 - \omega^2 LC} \quad (3)$$

There are various kinds of insertion coils; CMC was chosen for our study. A CMC is a carbon fiber wound in the shape of a coil with a pitch having dimensions on the order of micrometers to nanometers. The helical/spiral materials are expected to have novel functionality and many potential applications such as tunable micro-devices, sensors, electromagnetic absorbers, energy-changing materials, hydrogen absorbers, and chiral catalysts. We previously reported the improvement of a phantom’s electrical properties by the addition of CMC. However, the mechanism of this electrical property improvement by the addition of CMC was not clear. The elucidation of this mechanism is important for the high functionality of the phantom. Thus, we attempted to elucidate the principle by using carbon fiber, which was thought to function as an inductance, because CMC is expensive. Figure 4 shows a scanning electron microscopy (SEM) image of the carbon fiber that we used in this study.

The carbon fiber we chose had a fiber length of 130 $\mu$m and a bulk density of 350 kg/m$^3$. The self-inductance of the circular section of a cylindrical conductor is given in Eq. (4).

$$L = \frac{\mu_0 l}{8\pi} + \frac{\mu_l}{2\pi} \log \left( \frac{l + \sqrt{a^2 + l^2}}{a} \right) - \sqrt{a^2 + l^2} + a \quad (4)$$

where $l$, $a$, $\mu_0$, and $\mu_l$ are the conductor length, conductor radius, permeability of the material, and permeability of
vacuum, respectively. A phantom that contained carbon fiber added according to a conventional recipe (see Table 1), was produced experimentally. Figure 5 displays an SEM image of the carbon-fiber-added phantom. The carbon fiber was distributed in random directions inside the phantom. The electrical characteristics of the manufactured phantom were measured.

4. Measurement Results

4.1 Electrical properties of carbon-added phantom

Figures 6 and 7 show the relative permittivity and conductivity characteristics of the proposal phantom having the added carbon fiber\[18\]. The electrical properties of human muscle are included in Figs. 6 and 7 for reference \[19\].

The relative permittivity was increased by the addition of the carbon fiber. The added carbon fiber functioned as an inductance, although the effect as an inductance of carbon fiber depends on frequency. In particular, the relative permittivity of a phantom that had 2wt% carbon added agreed well with the literature in a frequency band greater than 5 MHz.

The conductivity increased with the addition of the carbon fiber. This was considered to be due to the effect of the carbon. A phantom could be fabricated in which the relative permittivity and conductivity values correspond to those of the muscle of a living body in the low-frequency band by further adjusting the quantity of NaCl.

According to the above results, the addition of the carbon fiber caused the relative permittivity of the phantom to increase. The next section considers whether the carbon fiber works as an inductance, or the electrical characteristics are improved by the addition of carbon material.

4.2 Comparison of carbon-fiber-added phantom and ground-carbon-fiber-added phantom

We ground the carbon fiber into a powder form by using a mortar. A phantom that included this ground carbon fiber was then designed experimentally. Figures 8 and 9 show the ground carbon fiber. The magnification of the SEM image in Fig. 8 is the same as that of Fig. 4. Most of the ground carbon fibers had lengths in the range of 10 $\mu$m to 100 $\mu$m (see Fig. 9). If the carbon fiber works as an inductance, the electrical characteristics would be improved. However, there was only a slight increase in the relative permittivity of the phantom to which the ground carbon fiber was added, when compared with the phantom to which unground carbon fiber was added.

Phantoms with carbon fiber as well as ground carbon fiber were designed experimentally. The relative permittivity and conductivity of these phantoms and the conventional one were then measured. The amounts of added carbon fiber and ground carbon fiber were 2 wt%. The measurement results of the relative permittivity and conductivity are shown in Figs. 10 and 11, respectively. Figure 12 shows the reduction ratio of the relative permittivity and conductivity between the original carbon-added phantom and the ground-carbon-fiber phantom.

The relative permittivity of the phantom with the added carbon fiber was increased when compared with that of the conventional phantom. On the other hand, the
The relative permittivity of the phantom with the added ground carbon fiber was decreased when compared with that of the original phantom with the added carbon fiber. According to the SEM images of the ground carbon fiber (Figs. 8 and 9), the fiber shape partially remained. As a result, the relative permittivity of the phantom with the added ground carbon fiber was higher than that of the conventional phantom. Therefore, it was revealed that the increase in the relative permittivity by the addition of the carbon fiber was caused by the inductance of the carbon fiber.

The conductivity of the phantom with the added ground carbon fiber was decreased compared with that of the carbon-fiber-added phantom and was similar to that of the conventional phantom. This carbon material had little effect on the conductivity characteristics of the phantom at the measured frequency range. It was revealed that the length of carbon fiber affected the conductivity of the carbon-fiber-added phantom. The characteristics of these manufactured phantoms were in good agreement with those of muscle tissue, which is the reference at the measured frequency range.

Fig. 8 SEM image of ground carbon (×80).

Fig. 9 SEM image of ground carbon (×600).

4.3 Comparison of carbon-added phantom and CMC-added phantom

The electrical properties of our previously proposed CMC-added phantom were compared to those of the carbon-added phantom. The amounts of added carbon fiber and CMC were 2 wt%. The relative permittivities and conductivities of the phantoms are shown in Figs. 13 and 14, respectively. The relative permittivities of CMC-added phantom and carbon-added phantom were similar. Generally, the inductances of coil-shaped
materials are higher than those of fiber-shaped materials. This shows the possibility that the windings of the CMC coils were shorted by the water of the high-hydrous phantom, and CMC thus behaved as a large fiber in the phantom.

The conductivity of the CMC-added phantom was greater than that of the carbon-added phantom. In this study, no comparison of the composition of the carbon was conducted. Therefore, this difference might have occurred because of a difference in the carbon. The details are problems for future examination.

4.4 Electrical properties at high-frequency band

We also evaluated the electrical characteristics of the manufacturer’s phantoms at a high-frequency band to evaluate whether the proposed phantoms are applicable for a wide band. A dielectric probe (Agilent Technology, 85070E, California, USA) and a network analyzer (Agilent technology, N5230A, California, USA) were used for the measurement at a frequency range of 200 MHz to 20 GHz. The complex relative permittivity is shown in Eq. (5). The real part $\varepsilon_r$ is the relative permittivity. The conductivity was calculated on the basis of the imaginary part of $\varepsilon_r$ (see Eq. (6)).

$$\varepsilon_r = \varepsilon'_r - j\varepsilon''_r$$

$$\sigma = \omega\varepsilon'_r$$

where $\omega$ is the angular frequency. Figures 15 and 16 show the relative permittivities and conductivities, respectively, of the conventional phantom and phantoms with added carbon fiber and added ground carbon fiber. The relative permittivity and conductivity of the carbon-added phantom were increased compared with those of the conventional phantom. On the other hand, the electrical properties of the ground-carbon-fiber added phantom were only slightly increased compared with that of the conventional phantom. It is thought that carbon fiber does not work as an inductance inside the phantom in the frequency range of 200 MHz to 20 GHz. In this range, the electrical properties of the conventional phantom were more similar to the reference than those of the carbon-added phantom. It is thought that the use of the conventional phantom would be more appropriate in this frequency band.

5. Conclusion

This paper described the improvement of the electrical properties of a phantom by the addition of carbon fiber. The mechanism of this improvement was also discussed. CMC and carbon fiber function as inductances inside a high-hydrous phantom at a low-frequency band. The relative permittivity of the phantom increased. Furthermore, the relative permittivity of a phantom to
which 2 wt% carbon was added was in good agreement with that of human muscle in the frequency range of 5 to 30 MHz. Because the trial manufacture of our proposed phantom only involved the addition of carbon fiber to a conventional high-hydrous phantom, the fabrication was easy. An evaluation of the electrical characteristic in the intermediate frequency band of 30—200 MHz will be considered in a future study.

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References


