Development of 500 kHz Muscle Equivalent Solid Phantom

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Abstract: Tissue-mimicking phantom is a biological tissue replacement which has been used as a replacement to understand the relationship between the electromagnetic and the human body. However, many of the developed phantoms are produced for several MHz to several GHz region, and less in the kHz region. This research introduces a new phantom to understand the electromagnetic effect at kHz region. The phantom is a 500 kHz phantom which mimics human muscle dielectric properties. The dielectric properties of the phantom are adjusted by aluminum powder content, which is 40% of the total phantoms content. In this research, we use different phantom dielectric properties measurement method compared to the one at higher frequencies. Furthermore, the phantom thermal properties and density are measured to be used in numerical calculations.

Keywords: radio frequency, muscle phantom, 500 kHz, dielectric properties, measurement method

Classification: Electromagnetic compatibility (EMC)

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1 Introduction

Various phantoms which simulate electrical characteristics equivalent have been developed and used to quantitively and qualitatively measure the interaction between the electromagnetic field and biological body. Measurement and experiments have been conducted in various fields, such as wireless communication system [1, 2], medical imaging system [3], and therapeutic application [4]. However, phantoms developed in recent years are mainly ranging from several MHz to several GHz, with rarely in kHz region.

Dielectric properties of a biological tissue changes with frequency. In the kHz region, the relative permittivity ($\varepsilon_r$) is higher compared to the MHz and GHz area. $\beta$-dispersion mainly responsible for the variation of dielectric properties around kHz region. The polar molecule in materials will reorient under the influence of an external electric field, thus contributing to the polarization and exhibiting a phenomenon called dielectric relaxation. The $\beta$-dispersion results from Maxwell-Wagner type relaxations resulting from the capacitive charging of cell membranes. At low frequencies, the charging for a cell membrane is small enough to charge and discharge the membrane completely during a single cycle. This caused a high tissue capacitance which leads to high dielectric properties. These high dielectric properties have caused producing a tissue-mimicking phantom at kHz frequencies difficult.

In our previous research, we proposed a radio frequency tissue-mimicking muscle phantom for device performance evaluation [5]. This paper presents the development and fabrication of muscle equivalent solid phantom at frequency of 500 kHz. RF current device uses high-frequency alternating current at several kHz (300-700 kHz). 500 kHz is chosen this frequency range has been traditionally utilized for electrosurgery devices, which served as predicate devices for RF ablation device such as an electrical scalpel. Also, at 500 kHz, the biological medium can be considered almost totally resistive. Cases where relative
permittivity important are body-centric wireless communications (BCWCs), implantable antenna and wireless capsule endoscopy (WCE). These cases show that relative permittivity affects the effective electrical length of the antenna, which causes difference in the received power. The dielectric properties of the developed phantom are based on the data references from [7, 8]. For the developed phantom data to be usable in various numerical calculations, we further measure the thermal properties and the material density.

2 Materials and phantom producing technique
The 500 kHz phantom was developed based on the human muscle properties at 500 kHz. The relative permittivity at lower frequencies is much higher than the one at higher frequencies such as microwave. The phantom is adjusted until the relative permittivity is within a 10% margin of error compared to references [6, 7].

The phantom is a water-based phantom made mostly using ionized water. Aluminum powder was used to adjust the relative permittivity (εr) of the phantom. Gellan gum was used to solidified phantom because it has a minimal effect to the change of the phantom dielectric properties. Although gellan gum has minimal effect on the dielectric properties, adding a great amount can affect not only dielectric properties but also rigidity of the phantom. The phantom can be solidified by using 1% of gellan gum of the total ingredient. However, because the aluminum powder was used, the necessary rigidity for the phantom to keep its shape could not be achieved, so the content ratio was increased. The gellan gum content ratio is set at 3% after consideration of dielectric properties effect and rigidity.

First, the gellan gum was melted using hot water. The temperature of the water was controlled between 60 °C and 100 °C. Boiling water was avoided because it can add bubbles when the phantom solidified. The gellan gum was stirred with hot water until the water became transparent and not diluted, with the viscosity changed. After that, the temperature was raised a little bit and poured into a plastic container. The aluminum powder then poured into the container and was mixed until the powder spread evenly. Finally, the container was closed, and the phantom was kept to solidifying at room temperature. In this research, the ratio of water and gellan gum is fixed, while the dielectric properties of the phantom were increased gradually using aluminum powder.

3 Measurement method
We used 6530B LCR meter (Wayne Kerr Electronics, Sussex, UK) to measure the dielectric properties of the developed phantom. After the under-development phantom solidifies, the phantom was sliced and then fitted inside an acrylic cylinder. When fitted, it is important to make sure less to no air inside the cylinder. Following that, both of the open sides of the cylinder are closed with electrodes. Finally, the under-development phantom dielectric properties are measured by the LCR meter. Fig. 1 shows the under development 500 kHz phantom measurement environment. Using LCR meter, the material impedance is measured, and from this data we calculated the relative permittivity and electrical conductivity of the
phantom. LCR meter reads out the $\varepsilon'$ and $\varepsilon''$ of measured phantom. $\varepsilon'$ represents relative permittivity, and $\varepsilon''$ is used to measure the conductivity ($\sigma$) using:

$$\sigma = \varepsilon'' \frac{2\pi f \varepsilon_0}{\varepsilon_0}$$

where $f$ is the frequency of interest and $\varepsilon_0$ is the permittivity of free space ($\varepsilon_0 = 8.854 \times 10^{-12} \text{ F m}^{-1}$).

After the developed phantom relative permittivity is within 10% of the reference data, the thermal properties and its material density is measured. For the thermal properties of the phantom, we asked the Agne Gijutsu Center for the measurement. Thermal conductivity is measured using thermal conductivity analyzer ARC-TC-1000 (Agne, Yokohama, Japan). Also, specific heat capacity is measured using specific heat measurement system SH-3000 (Advance Riko, Tokyo, Japan).

![Measurement of the phantom using LCR meter.](image)

**Fig. 1.** Measurement of the phantom using LCR meter.

### 4 Measurement results

Fig. 2 shows the measurement results after adjusting the aluminum powder content and making the water and gellan gum ratio fixed. In Fig. 2, the data of human muscle and porcine liver are based on the [6, 7]. Aluminum powder increase between 1% ($\varepsilon_r = 141$) and 8% ($\varepsilon_r = 817$) roughly translates to a 1% increase of aluminum powder and equals relative permittivity increase of $\varepsilon_r$ to around 100. A gradual increase of aluminum powder also means a gradual increase of phantom’s $\sigma$. This is shown by gradual increase from 1% of aluminum to 20%, from $\sigma = 0.22 \text{ S/m}$ to $\sigma = 0.48 \text{ S/m}$, respectively. 40% of aluminum powder phantom’s relative permittivity ($\varepsilon_r = 3,629$) matches human muscle, albeit over increase of conductivity ($\sigma = 0.57 \text{ S/m}$). Decrease of conductivity ($\sigma$) from 35% aluminum ($\sigma = 0.57 \text{ S/m}$) to 40% aluminum ($\sigma = 0.53 \text{ S/m}$) can be considered as an error when mixing aluminum with gellan gum and water. The necessary relative permittivity and electrical conductivity of phantom achieved with the combination of aluminum powder (40%), ionized water (57%) and gellan gum (3%).
In this paper, we developed and measured a muscle phantom at 500 kHz. This phantom is developed using water, aluminum powder, and gellan gum as its ingredient. The relative permittivity of the phantom is 3,629, and within 10% variation compared to the literature. In addition, we measured the thermal properties and material density of the phantom. The developed muscle phantom relative permittivity and electric conductivity matches with the references and is suitable for various experiments and measurements.

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