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Development of electromagnetic phantom at low-frequency band

T. Yamamoto, K. Sano, K. Koshiji, X. Chen, S. Yang, M. Abe, and A. Fukuda

Abstract—**This paper describes the development of a human electrical phantom at a low-frequency band. The conventional highly hydrous electromagnetic phantom does not mimic the electrical properties of a living body. The electrical properties of the newly developed phantom, by adding a carbon microcoil (CMC) and NaCl to the conventional phantom, are in good agreement with those of a living body. In addition, the electrical properties of the phantom with a CMC and twice the amount of NaCl added are evaluated at frequency bands above 300 MHz, similar to the conventional highly hydrous gel phantom. The results show that the newly developed phantom can effectively function in the conventional target frequency band by a simple mechanism.**

I. INTRODUCTION

Phantoms [1-6] that imitate the electrical properties of a living body are widely used as substitutes for animals in experiments. These have been actively studied in various research institutions, and various types of phantoms have been developed, such as liquid phantoms [2], dry phantoms [3], and highly hydrous gel phantoms[1, 4, 5]. The highly hydrous phantom, which is mainly composed of deionized water, is orthopedically easy to operate while retaining the desired form, and it can imitate the broadband electrical properties of a living body. For this reason, it is useful in many applications.

The widely used composition of a conventional highly hydrous phantom is described. This type of phantom was originally developed to evaluate the specific absorption rate (SAR) of the human head when a person uses a mobile phone [5]. The electrical properties of this phantom are in agreement with the muscular electrical properties at frequency bands above 300 MHz, as reported in the literature. However, the electrical properties at frequency bands below 300 MHz have not been fully investigated. For example, although the phantom can be applied to a living human body considered to be a body area network (BAN) [7], in some BAN studies, a phantom that can be used at a frequency of 10 MHz is required. Radio frequency identification (RFID) studies employ a frequency of 13.56 MHz. In this paper, we report the development of an electromagnetic phantom at a low-frequency band below 30 MHz. In addition, we report the evaluation of the electrical properties of the newly developed phantom at frequency bands above 300 MHz, similar to the conventional highly hydrous gel phantom.

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T. Yamamoto, K. Sano, and K. Koshiji are with the Department of Electrical Engineering, Faculty of Science and Technology, Tokyo University of Science, Chiba, Japan. (phone: +81-4-7124-1501; fax: +81-4-7120-1741; e-mail: yamamoto@ rs.noda.tus.ac.jp).

X. Chen, S. Yang, and M. Abe are with the Department of Pure and Applied Chemistry, Faculty of Science and Technology, Tokyo University of Science, Chiba, Japan.

A. Fukuda is with the Department of Mathematical Information Science, Faculty of Science and Technology, Tokyo University of Science, Tokyo, Japan.

II. ELECTRICAL PROPERTIES OF CONVENTIONAL AND CMC-ADDED PHANTOMS

According to a particular reference [5], a highly hydrous gel phantom was first developed as an experimental one. The composition of the phantom is summarized in Table 1. The polyethylene powder for the adjustment of the permittivity, NaCl for the adjustment of the conductivity, agar for forming, TX-151 as a thickener, and sodium dehydroacetate monohydrate as an antiseptic are prepared using purified water, which is the main material.

TABLE I. COMPOSITION OF CONVENTIONAL PHANTOM

Materials	Weight [g]	Effects
Purified water	3375	Main material
Polyethylene powder	337.5	Relative permittivity
NaCl	19.6	Conductivity
Agar	104.6	Forming
TX-151	82.93	Thickener
Sodium dehydroacetate monohydrate	2.0	Antiseptic

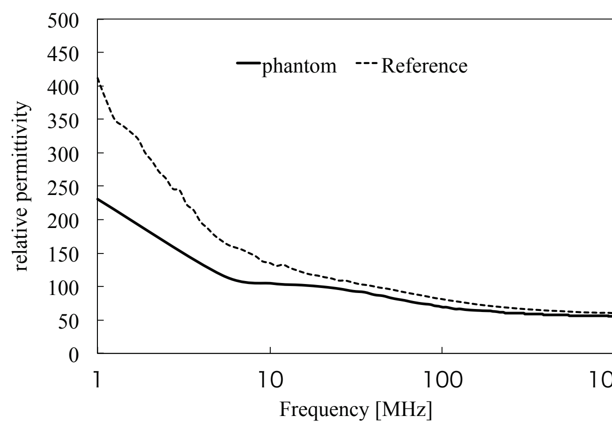

Fig. 1. Relative permittivity of conventional phantom.

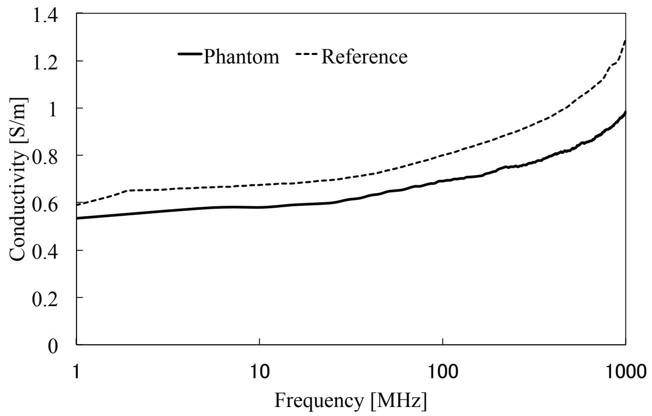

Fig. 2. Conductivity of conventional phantom.

The characteristics of the relative permittivity and conductivity of the conventional phantom and those of a living body [8] are compared. The electrical properties of the phantom are evaluated by using a coaxial tube method. The results are shown in Figs. 1 and 2. The main target frequency band of the conventional phantom is above 300 MHz. The relative permittivity and conductivity of the phantom are in agreement with the reference [8] at above 30 MHz. However, the electrical properties of the phantom are not in agreement below 30 MHz. The change in the dielectric properties at this frequency band is caused by beta dispersion owing to the phantom structure in the cell period. On the other hand, the relative permittivity of the phantom that does not have the structure in a period does not increase. According to a previous study, it is impossible for the electrical properties of the phantom to agree with those of a living body at a low-frequency band only by the adjustment of the materials used, as listed in Table 1, to develop the phantom. Therefore, the improvement of the electrical properties of the phantom at a low-frequency band is investigated by using new materials.

III. Measurement Method

At a low-frequency band, the electrical properties of the phantom are measured by using the method on the basis of the principle of a parallel plate capacitor. Figure 3 shows the measurement test fixture. It consists of two circular copper plates (50 mm in diameter). A polytetrafluoroethylene (PTFE) guide is employed to prevent misalignment between the metal plates.

The phantom is inserted between the two metal plates to obtain a parallel arrangement. For this reason, the phantom is sliced with a business-use meat slicer (Yasukichi, PRO-300ES-B, Gifu, Japan). Although the thickness of the phantom varies with the samples, it is set to 0.6–1.0 mm.

The relative permittivity and conductivity are computed using equations (1) and (2) from the measured value of Cp-Rp, which denotes the resistance and capacitance connected in parallel (see Fig. 4), obtained with an impedance analyzer (Agilent Technology, 4294A, California, USA).

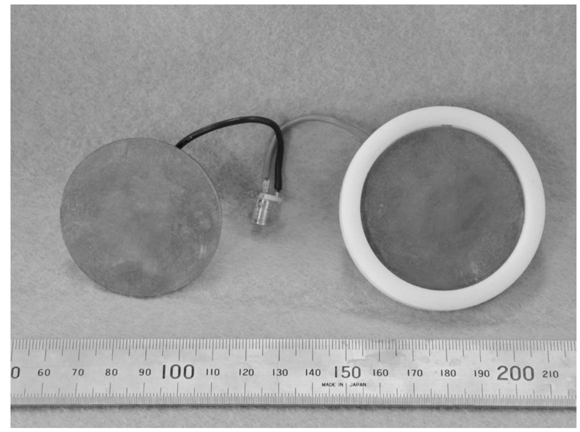

Fig. 3. Test fixture used at a low-frequency band.

$$\varepsilon' = \frac{Cd}{\varepsilon_0 S} \quad (1)$$

$$\sigma = \frac{d}{RS} \quad (2)$$

where d, S, and ε_0 are the distance between the parallel plates, electrode area, and permittivity of vacuum (8.854×10^{-12} F/m), respectively.

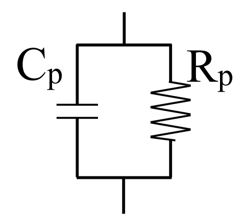

Fig. 4. Equivalent circuit for measurement

IV. Electrical Properties of Conventional And CMC-Added Phantoms

A carbon microcoil (CMC) [9-12] is added to the conventional highly hydrous phantom. The CMC is a carbon fiber wound in the shape of a coil with a micrometer- or nanometer-order pitch. The helical/spiral structure is expected to have a novel functionality and many potential applications such as tunable microdevices, sensors, electromagnetic absorbers, energy-changing materials, hydrogen absorbers, and chiral catalysts. The amount of CMC added is 2.5% by weight. Figures 5 and 6 show the relative permittivities and conductivities of the conventional and CMC-added phantoms.

The relative permittivity of the trial phantom increases, by the addition of the CMC, in the range of 1~20 MHz. The conductivity of the phantom increases, by the addition of the CMC, at or above 1 MHz. Although the relative permittivity of the phantom is approximated to the value of the reference [8] at or below 5 MHz by the addition of the CMC, the conductivity of the phantom is lower than that of the reference. Therefore, the phantom with an increased amount of NaCl is experimentally developed to improve the conductivity and the measurement is performed again. The electrical properties of the phantom developed with twice the amount of NaCl and those of the phantom with twice the amount of NaCl and CMC are measured. The results are shown in Figs. 7 and 8. Table 2 lists the composition of the phantom with twice the amount of NaCl and CMC.

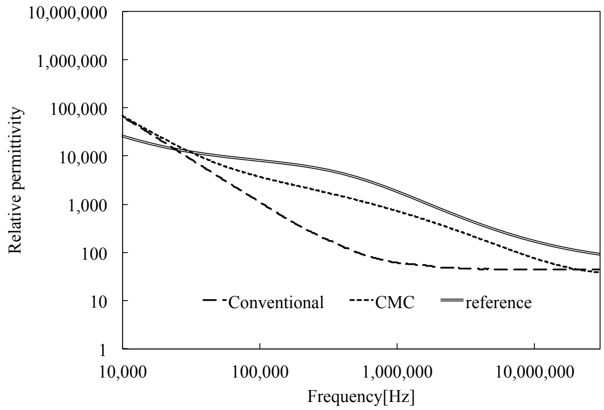

Fig. 5. Relative permittivities of CMC-added and conventional phantoms.

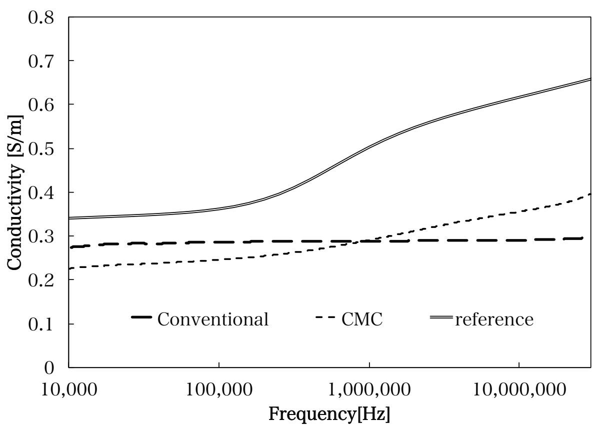

Fig. 6. Conductivities of CMC-added and conventional phantoms.

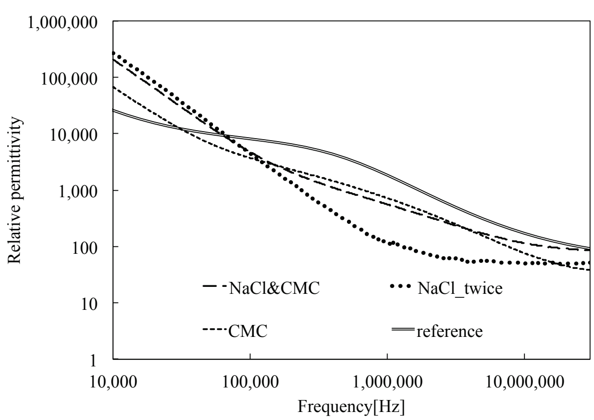

Fig. 7. Relative permittivity of improved phantom.

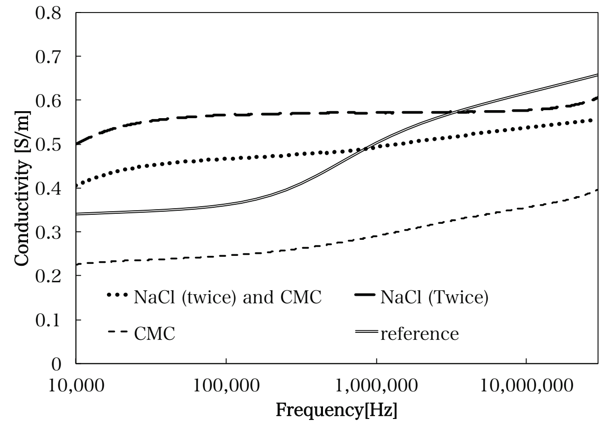

Fig. 8. Conductivity of improved phantom.

TABLE II. RECIPE OF CMC AND TWICE NACL ADDITION PHANTOM

Materials	Weight [g]	Effects
Deionized water	580	Main material
Polyethylene powder	56	Relative permittivity
NaCl	6.0	Conductivity
Agar	17	Forming
TX-151	14	Thickener
CMC	8.3	Relative permittivity (new added)

The conductivity of the phantom with a CMC and twice the amount of NaCl added increases and approaches the reference level and almost agrees at approximately 1 MHz.

The relative permittivity of the phantom with a CMC and twice the amount of NaCl added when compared with the phantom with twice the amount of NaCl added is obtained at a frequency below 100 kHz. The characteristics of the conventional phantom and CMC-added phantom are similar at or below 100 kHz. This effect is attributed to the addition of NaCl. On the other hand, the relative permittivity of the phantom with a CMC and twice the amount of NaCl added when compared with the CMC-added phantom is obtained at a frequency range above 100 kHz. The results show that the addition of CMC is effective for the improvement of the dielectric constant at this frequency band.

V. ELECTRICAL PROPERTIES AT HIGH-FREQUENCY BANDS

The conventional phantom targets frequency bands above 300 MHz. The relative permittivity and conductivity of the phantom with added CMC and twice the amount of NaCl at these frequency bands are evaluated. A dielectric probe (Agilent Technology, 85070E, California, USA) and a network analyzer (Agilent technology, N5230A, California, USA) are used for the measurement in the frequency range from 200 MHz to 20 GHz. Figures. 9 and 10 show the measurement results of the relative permittivity and conductivity of the phantoms, respectively.

The relative permittivity of the phantom with the addition of a CMC and twice the amount of NaCl increases in comparison with that of the conventional phantom. However, the measurement results of the phantom agree with the reference, with less than 10% of error at a frequency band above 1 GHz. Additionally, the conductivity of the phantom with the addition of a CMC and twice the amount of NaCl increases in comparison with the conventional phantom. The measurement results of the newly developed phantom agree with the reference, with less than 25% of error at all of the measurement frequency bands. The newly developed phantom, described in this paper, can function effectively at the conventional target frequency band by a simple use.

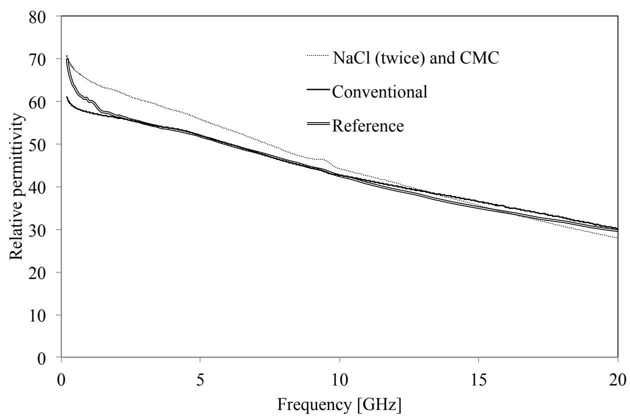

Fig. 12. Relative permittivity characteristics of the phantom with added CMC and twice the amount of NaCl at a high-frequency band.

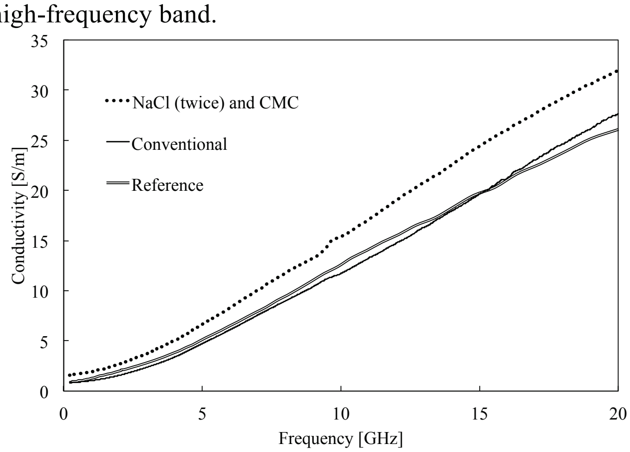

Fig. 13. Conductivity characteristics of the phantom with added twice the amount of NaCl and CMC at the high-frequency band.

VI. CONCLUSION

In this study, we have investigated the improvement in the electrical properties of a highly hydrous gel phantom comprising a CMC at low-frequency bands. We have proved that the conventional highly hydrous gel phantom does not mimic the electrical properties of the muscles of a living body at frequency bands below 30 MHz. A CMC is added to the conventional phantom to increase the relative permittivity of the phantom. Furthermore, we have determined the amount of NaCl to be added in order for the conductivity of the phantom to agree with the reference. As a result, a phantom with electrical characteristics close to those of a living body is realized at approximately 1 MHz.

The electrical properties of the phantom with the addition of a CMC and twice the amount of NaCl are evaluated at frequency bands above 300 MHz, similar to the conventional highly hydrous gel phantom. The results show that the newly developed phantom, described in this paper, can function effectively at the conventional target frequency band by a simple mechanism.

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