DIY electromagnetic phantoms for biomedical wireless power transfer experiments

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DIY Electromagnetic Phantoms for Biomedical Wireless Power Transfer Experiments

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Abstract—To perform biomedical Wireless Power Transfer experiments at UHF and microwave frequencies, a need exists for recipes and procedures to construct human tissue mimicking phantoms. This paper outlines the procedure for realizing body-mimicking phantoms and provides some recipes based on demineralized water, sugar (sucrose) and salt (NaCl). Even without using preservatives all samples made for this research maintained the dielectric characteristics for at least ten days when stored at room temperature. A procedure to construct a low-cost RG405 semi-rigid coaxial waveguide-based measurement probe and calibration method are discussed as well. The absolute error in obtained relative permittivity, using this probe, relative to using a Commercially Off The Shelf probe is less than 2.0.

Keywords—Wireless Power Transfer, phantom, permittivity, measurement

I. INTRODUCTION

The remote RF powering of biomedical implants traditionally uses low frequencies, typically below 10 MHz. This choice is dictated by the assumed tissue absorption loss that is increasing with frequency [1, 2]. This low-frequency assumption justifies a quasi-static analysis (omitting the displacement current) that further confirms the initial loss assumption. However, incorporating the displacement current in the analysis leads to an optimal operating frequency that can be in the GHz-range [1, 2].

To validate and reproduce the work reported in [1, 2], we have designed several transmit and receive coils spanning a frequency range from 100 MHz to 2.7 GHz, see Figure 1.

Next to performing full-wave analyses, we also want to perform experiments. To make these experiments reproducible we want to avoid the use of beef [1] and use human tissue mimicking phantoms [3] instead.

Fig. 1. Printed coils. (a) 100 MHz (50mm x 50mm). (b) 500 MHz (10mm x 10mm). (c) 2.7 GHz (2mm x 2mm). of a figure caption.

However, instructions on how to make phantom material, mimicking a certain tissue for a certain frequency is hard to find. The few papers that are available, for example [4], are either limited in applicability or use exotic, hard to obtain ingredients. Furthermore, little can be found on stability, preparation, handling and storage-life of the phantom material. Therefore, we have set up a research on making and using phantom materials as well as measuring the complex permittivity of these materials. We think that the outcome of this research is of interest to a wide portion of the WPT community.

The organization of the paper is as follows: In Section II we will briefly describe how to measure complex permittivity and then will give the recipes to produce tissue mimicking fluids and gels. Here we will also indicate how the recipes will change to tune for different tissues and/or different frequencies and we will discuss the storage-life of the material. In Section III we will describe how to make a permittivity measurement probe from a piece of semi-rigid coaxial cable and how to calibrate it, avoiding the use of a short. Not only will this allow for an alternative to a Commercially Off The Shelf (COTS) measurement probe, it will also allow for low-budget, disposable measurement probes that can be incorporated in phantoms for monitoring the permittivity over time.

II. PHANTOM RECIPES

To create phantom fluids and gels we only want to use products available in general supermarkets. So, as a basis we will use demineralized water. We will add agar or gelatin to produce jelly-like or self-shaping phantoms. We will add sodium chloride (table salt) to tune the conductivity and sugar to tune the real part of the relative permittivity. We have not attempted to use sodium azide as a preservative. Sodium azide is poisonous and due to its recent web-recommended use for suicide, very difficult to acquire; two reasons not to use it. As will be shown, we have found that it is perfectly possible to create phantoms with a fair storage life without using preservatives.

A. Permittivity Measurement

Before going into the recipes and procedures to create body tissue mimicking fluids and gels, we first need to discuss the measurement of the relative permittivity. Relative permittivity is a complex quantity:

$$\epsilon_r = \frac{\epsilon(\omega)}{\epsilon_0} = \epsilon'_r(\omega) + j\epsilon''_r(\omega) = \epsilon'_r(\omega) + j\frac{\sigma}{\omega\epsilon_0}, \quad (1)$$

where ω is the angular frequency, ϵ_0 is the free space permittivity and σ is the conductivity of the medium.

Measurement of the complex permittivity of fluids and gels is best performed by measuring the complex reflection coefficient of an open-ended coaxial line, thus obtaining the aperture admittance [5]. A calibration using three standards, usually incorporating water, air (open) and a short, is needed before measurement of the material under investigation can be performed.

For our measurements we have made use of the Keysight 85070E High Temperature probe [6] (open-ended coaxial line) attached to a Keysight E5061B Vector Network Analyzer (VNA) [7], see Figure 2. The probe is connected to the VNA using a phase-stable coaxial cable. For correct results it is also important that all calibration standards and fluids as well as the test sample are on the same temperature. Leaving everything overnight in the test laboratory is an easy way to accomplish this.

Fig. 2. Permittivity measurement. (a) Keysight 85070E High Temperature probe. (b) Different samples for measurement.

B. Creating the Phantom Material

To create the phantom-material we start with heating a large supply of demineralized water. We keep the temperature just below 100° Celsius (not cooking). This temperature is not overly critical. It needs to be in excess of 40° Celsius to dissolve gelatin and in excess of 95° Celsius to dissolve agar. Gelatin is added to create a jelly-like structure; agar is added to make the phantom material solid. We need about 40g/l agar to create a solid phantom.

Next, a desired quantity (grams or milliliters) is taken from this heated water supply and put into a separate container. Then, the right quantities (masses) of sugar and salt are added. The ingredients are thoroughly mixed using a hand-held electrical blender. In this process, gelatin or agar can be added in an amount to be determined visually (stop adding gelatin or agar if the right degree of ‘jellyness’ or solidity is reached). The container with the solution is then closed and left to cool down, see Figure 2(b). Closing is important for maintaining the desired permittivity; not closing the container leads to evaporation and a severe change of permittivity.

C. Recipes

To test how different concentrations of salt and sugar influence permittivity, we have first changed the sugar (weight) concentration and measured the relative permittivity for two frequencies: 400 MHz and 2.45 GHz. We have measured different samples to test reproducibility and have measured on several days after producing the samples to test for storage-life. In all solutions we have applied gelatin in a concentration of 24 gram per liter and salt in a concentration of 20 gram per liter. Figure 3 shows the real part of the relative permittivity as a function of sugar concentration. Figure 4 shows the conductivity as a function of sugar concentration.

We do see an excellent reproducibility, proving the correctness of the mixing procedure and a storage time (at room temperature) of at least three days (in fact, none of our many samples changed in relative permittivity value within the first ten days after production). We also see that adding sugar decreases both the real and imaginary part of the relative permittivity.

Figure 5 shows the real part of the relative permittivity as a function of sugar (weight) concentration for different salt (weight) concentrations at a frequency of 2.45 GHz. Figure 6 shows the conductivity vs. sugar concentration at 2.45 GHz. Figure 7 shows the conductivity as a function of salt (weight) concentration for two values of the sugar (weight) concentration at 2.45 GHz.

These graphs confirm that adding sugar decreases the real part of the permittivity and – in general – the imaginary part of the relative permittivity as well and that adding salt increases the conductivity.

Fig. 3. Real part relative permittivity as a function of sugar (weight) concentration (a) 400 MHz. (b) 2.45 GHz.

Fig. 4. Conductivity as a function of sugar (weight) concentration (a) 400 MHz. (b) 2.45 GHz.

Fig. 5. Real part relative permittivity as a function of sugar (weight) concentration for different salt (weight) concentrations.

Fig. 6. Conductivity as a function of sugar (weight) concentration for different salt (weight) concentrations.

Fig. 7. Conductivity as a function of salt (weight) concentration for different sugar(weight) concentrations.

The graphs indicate that water with sugar and salt in the right concentrations can be used to mimic human tissue and that even without the use of preservatives the dielectric characteristics will remain stable for several days. As said, none of our samples, stored at room temperature, did start to deviate earlier than ten days after preparation.

Based on the acquired knowledge we have created phantoms mimicking the relative permittivity of muscle, stomach and kidney tissue as well as blood for the frequencies 433 MHz, 915 MHz and 2450 MHz [8]. The recipes are stated in Table I.

TABLE I. PHANTOM RECIPES

Tissue	Freq. (MHz)	Permittivity [8]	conductivity (Sm ⁻¹)	weight (%) sugar	weight (%) NaCl
Muscle	433	56.9	0.805	48.0	1.55
Muscle	915	55.0	0.948	43.5	0.65
Stomach	433	67.2	1.01	31.0	1.00
Stomach	915	65.0	1.19	31.0	0.80
Stomach	2450	62.2	2.21	26.5	0.00
Blood	433	63.8	1.36	36.5	2.10
Blood	915	61.3	1.54	34.5	1.55
Blood	2450	58.3	2.54	31.0	0.35
Kidney	433	65.5	1.12	34.0	1.40
Kidney	915	58.6	1.40	38.0	1.55
Kidney	2450	52.7	2.43	37.0	0.10

Specifically aimed for the MedRadio band (401-406 MHz), the recipes for muscle and stomach mimicking phantoms are stated – with more detail - in Table II.

TABLE II. PHANTOM RECIPES FOR 402 MHz (24 GRAM GELATINE PER 1000 GRAM DEMINERALIZED WATER)

Biological Tissue	Permittivity [8]	conductivity (Sm ⁻¹)	gram (%) sugar	gram (%) NaCl
Muscle	58.8	0.84	928 (47)	22.7 (1.15)
Stomach	67.5	1.0	446 (30)	17.1 (1.15)

Figures 8 and 9 show the measured values of the real part of the permittivity and the conductivity as a function of frequency for both phantom materials based on the recipes in Table II, demonstrating the correctness of the recipes.

Fig. 8. Measured value of the real part of the relative permittivity as a function of frequency (A = Muscle mimicking phantom, D = Stomach mimicking phantom).

Fig. 9. Measured value of the conductivity as a function of frequency (A = Muscle mimicking phantom, D = Stomach mimicking phantom).

III. DIY PROBE

Our COTS measurement probe got damaged beyond repair, mainly due to the attachment of the short-calibration-piece. Therefore, we have developed our own measurement probes, based on RG405 semi-rigid coaxial cable, see Figure 10. These probes are so low-cost (about 5 € a piece) that we can use them as integral and disposable part of our phantoms to monitor the relative permittivity over time.

Fig. 10. Measurement probe constructed from a piece of RG405 semi-rigid coaxial cable with assembled SMA connectors.

A multitool with a grinding disk was used to slowly cut the cable with two assembled SMA connectors (carefully held into a vice) in half. After that, the multitool with a sanding bit was used to sand both open ends of the coaxial cable smooth and flat. (Sanding can be performed again to renew the probe after it has been used for some time).

The measurement procedure follows the procedure described in [5]. For the calibration, three references are needed. Usually for these references, air (open), deionized water and a short are used. Here, we have circumvented the use of a short since this would require a precise mechanical attachment. Instead we have chosen for a second liquid next to deionized water.

A. Calibration Liquid

For the calibration liquid we need to have a liquid with a high, known conductivity (using ethanol did not work for our measurements due to the low conductivity). The liquid we have used is made by adding 928 g sugar (sucrose) and 22.7 g of salt (NaCl) to 1000 g of deionized water.

The relative permittivity of this liquid has been measured using a Keysight 85070E High Temperature probe and is fitted as a function of frequency f ($3.0 \cdot 10^7 \text{ Hz} \leq f \leq 3.0 \cdot 10^8 \text{ Hz}$) by

$$\epsilon_r = \sum_{n=0}^7 p_n f^n, \quad (2)$$

Where the polynomial coefficients p_n ($n = 1, 2, \dots, 7$) are given by

$$\begin{aligned} p_0 &= 66.8053 - j68.4170, \\ p_1 &= -2.1881 \cdot 10^{-8} + j1.9371 \cdot 10^{-7}, \\ p_2 &= 1.2322 \cdot 10^{-17} - j3.4940 \cdot 10^{-16}, \\ p_3 &= -5.4360 \cdot 10^{-27} + j3.5044 \cdot 10^{-25}, \\ p_4 &= 1.3400 \cdot 10^{-36} - j2.0694 \cdot 10^{-34}, \\ p_5 &= -1.3543 \cdot 10^{-46} + j7.1345 \cdot 10^{-44}, \\ p_6 &= -j1.3268 \cdot 10^{-53}, \\ p_7 &= j1.0274 \cdot 10^{-63}. \end{aligned} \quad (3)$$

In performing the calibration, using liquids, care must be taken in avoiding the forming of air bubbles on the surface of the probe. These bubbles might be difficult to spot. To make sure that the calibration is performed well, best perform a calibration measurement, clean the probe (using deionized water other than the reference deionized water) and repeat the measurement. If the results are not identical, most probably air bubbles were formed on the surface of the probe.

B. Measurement

For measuring (as well as calibration), the probe is fixed in a holder and samples are placed under the probe, submerging the probe into the liquid, see Figure 11.

Fig. 11. Application of the DIY probe. The probe is fixed in position and attached to the VNA using a phase-stable cable. Measurement samples are brought underneath the probe such that the probe aperture is submerged into the sample.

For measurements, we advise to have the tip of the probe at least 5 mm submerged and at least 10 mm displaced from the walls and/or bottom of the sample container.

After each measurement, the probe must be wiped clean with a tissue, cleaned using deionized water and wiped dry.

Figure 12(a) shows the real and imaginary part of the relative permittivity as a function of frequency of a sample of (contaminated) ethanol. The relative permittivity values are obtained through measuring with a COTS-probe [6] and processing with the accompanying software as well as by measuring with the DIY probe and processing following the theory of [5]. Figure 12(b) shows the error in the DIY-probe measurements relative to the COTS-probe measurements.

Figure 13(a) shows the relative permittivity vs. frequency for a sample taken from a mixture of 908 g sugar dissolved in 1000 g demineralizer water. The values are measured using a COTS-probe [6] and measured using the DIY probe. Figure 13(b) shows the error in the DIY-probe measurements relative to the COTS-probe measurements.

(a)

(b)

Fig. 12. Relative permittivity of (contaminated) ethanol vs. frequency. (a) Values measured with a RG405-based DIY probe and measured with a Keysight 85070E High Temperature Probe. (b) Error of DIY probe measurement values relative to the Keysight probe measurements.

(a)

(b)

Fig. 13. Relative permittivity of sugar-water-mixture vs. frequency. (a) Values measured with a RG405-based DIY probe and measured with a Keysight 85070E High Temperature Probe. (b) Error of DIY probe measurement values relative to the Keysight probe measurements.

IV. CONCLUSIONS

It has been shown that it is possible to create body-tissue-mimicking fluids, for frequencies ranging from UHF to microwaves, by mixing demineralized water, sugar and salt in the right proportions. By adding gelatin, the fluid can be made jelly-like. By adding agar, the solution can be made solid. Even without adding preservatives, all samples made for this research maintained the dielectric characteristics for at least ten days when stored at room temperature.

Low-cost permittivity measurement probes can be easily constructed from pieces of RG405, semi-rigid coaxial waveguide. Calibration needs air (open), deionized water and a sugar-salt-water mixture. Measured reflection data needs to be processed following a procedure described in [5]. The maximum absolute error relative to a using a COTS probe and software is less than 2.0

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