Formulas for Easy-To-Prepare Tailored Phantoms at 2.4 GHz ISM Band

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***Abstract*—Emerging integration of communication networks into wearable or implantable body devices involves a challenge due to the transmitting medium, the body itself. This medium is heterogeneous and lossier than air, so devices that are supposed to work on it should be tested in tissue-equivalent materials. A number of materials with the electromagnetic response of body tissues have been proposed. Most of them are sucrose aqueous solutions that are supposed to simulate human's muscle tissue mainly within medical frequency bands. However, these recipes are restricted to a single tissue and it is difficult to adapt them to fit the permittivity values of different body tissues. The significance of this study lies in the development of a mathematical relationship that models the dielectric properties of an aqueous solution according to the concentration of sugar and salt at 2.4 GHz, the frequency around which an Industrial, Scientific and Medical (ISM) band is placed. Thus, it becomes possible to create custom-made phantoms with simple and accessible ingredients that are easy to prepare in any laboratory.**

Keywords*—body area network (BAN); coaxial probe; dielectric; industrial, scientific and medical (ISM) band; phantom

I. INTRODUCTION

Wireless communications keep growing into new environments inasmuch as they are able to work where wires don't reach. One of the examples is the integration in the body itself of the so-called body area networks (BANs). Medical applications are the intended fate of these BANs, which use would be the monitoring of vital signs with the aid of body-implanted sensors. IEEE defines BANs as a standard of communications optimized for low power devices which operate within human's body environment to target medical applications, consumer electronics or personal entertainment [1]. This technology demands new devices that must be designed specifically for working throughout human body, which acts as transmission medium for electromagnetic waves. Moreover, in order to improve their design and performance, these appliances need to be tested in their intended medium. Instead of turning to human testing, a workable solution is to choose synthetic tissues that model the signal losses in the human medium, so that experiments are simple, cheap and reproducible. Human body is a heterogeneous medium composed of a great deal of different tissues with varying properties that are far from air, in particular their relative permittivity, which is quite higher in most tissues.

Relative permittivity, ε_r, is the property of materials or media that determines how electromagnetic waves propagate through them [2]. It consists of two components: a real one, ε_r', known as dielectric constant, which indicates how much energy is stored by the material when an electric field is applied to, and the imaginary part, ε_r'', called loss factor, which is related to the loss of energy by various mechanisms such as electric conductivity.

Regarding the modeling of the electromagnetic human body behavior, there are a number of contributions that propose formulas for preparing tissue-equivalent solutions, usually known as phantoms. Taking real measurements of human tissues [3], [4] as reference, these works often suggest sucrose as main ingredient [5], [6] to imitate particular tissues within radiofrequency bands. These solutions are usually combined with agar [7], [8] or other gelling agents [9], [10] with the aim of getting a semisolid model. Other works also suggest to add different compounds such as vegetable oil and flour [11], polyethylene powder [12], or diethylene glycol monobutyl ether [13] to tune the phantoms. The suitability of a phantom depends on the frequency and the targeted tissue. Inasmuch as these phantoms are intended to test biomedical applications, most of these formulas are given for authorized ISM bands [14]. However, the reported formulas are given for a few tissues and include ingredients that are not always available in wireless communications laboratories.

The main purpose of this work is to provide tools to design phantoms with cheap and accessible ingredients within the 2.4 GHz ISM band. This aim is attempted by means of a mathematical model of solutions of sugar and salt, which is not available in the literature. These compounds are the main proposed ingredients in reported specific phantoms. Since the number of available tissues must be broaden for testing future BAN devices, we present an extensive combination of these compounds in addition to accurate formulas in order to prepare adjustable phantoms. We have focused on the 2.4 GHz ISM band for the purpose of biomedical applications, hereinafter ISM band, which is widely used in BAN applications. It is a communications standard allowed to be used without a specific license in the vast majority of countries. However, the dielectric characterization is presented in a wider band in order to provide information for potential phantoms at multiple frequencies.

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II. EXPERIMENTAL SETUP AND MEASUREMENT METHODOLOGY

For the characterization of the phantom dielectric properties, an open-ended coaxial probe was used [15], [16]. This measurement technique is based on the determination of the reflection coefficient (S_{11}), a parameter directly related to the relative permittivity (1), which can be calculated from the previous one.

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \tag{1}$$

The imaginary part of relative permittivity is usually expressed as dielectric conductivity, σ_d (2):

$$\sigma_d = 2\pi \cdot f \cdot \varepsilon_0 \cdot \varepsilon_r'' \tag{2}$$

where f is the frequency of the applied field and ε_0 is the vacuum permittivity. It is important to distinguish it from electric conductivity inasmuch as the latter is included in the former.

Our measurement system consists of a vector network analyzer (Keysight ENA E5072A VNA) with a frequency range from 30 kHz to 8.5 GHz, a 1 m length coaxial cable, a coaxial probe (Keysight 85070E slim form probe) whose operation frequency is comprised between 500 MHz and 50 GHz, and a computer connected to the VNA by USB. The computer includes software to calculate the complex permittivity from the reflection coefficients. The slim form probe was connected to one of the ports of the VNA by a coaxial cable. As auxiliary supports, we used a bracket with a plier that held the coaxial probe standing, and a sample elevator to avoid fixture movements (fig. 1).

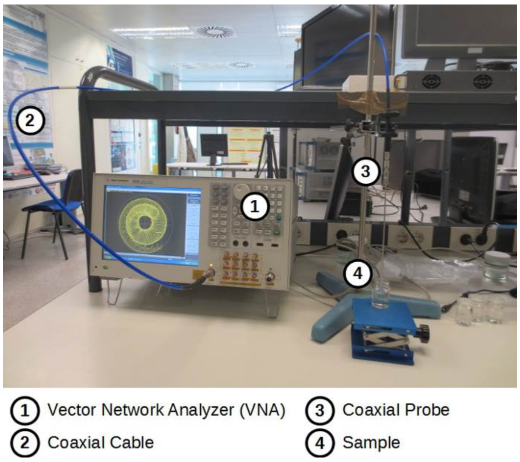

Fig. 1. Setup of the coaxial probe connected to the vector network analyzer.

Samples were scanned between 500 MHz and 8.5 GHz. 1601 points were recorded at each frequency sweep, thus the resolution frequency was 5 MHz. The output power was set at 10 dBm and the IF bandwidth to 1 kHz. In order to estimate the relative permittivity from the S_{11} parameter, the system was calibrated with air, deionized water, methanol (99.8%, Sigma-Aldrich), and a coaxial short. Measurements were performed by immersing the probe in the liquid samples, avoiding the presence of air bubbles at 24 degrees Celsius. The coaxial probe was cleaned between measurements with deionized water and lab paper.

III. RESULTS

A. *Analysis of the relationship between the permittivity and the addition of sugar and salt*

Fig. 2 shows the dielectric constant and conductivity of water with a 0%wt sucrose concentration (without sucrose) and varying salt concentrations. It can be observed that the dielectric constant progressively decreases with the addition of salt due to the decrease of water in the solution, which has a higher polarization capability than salt.

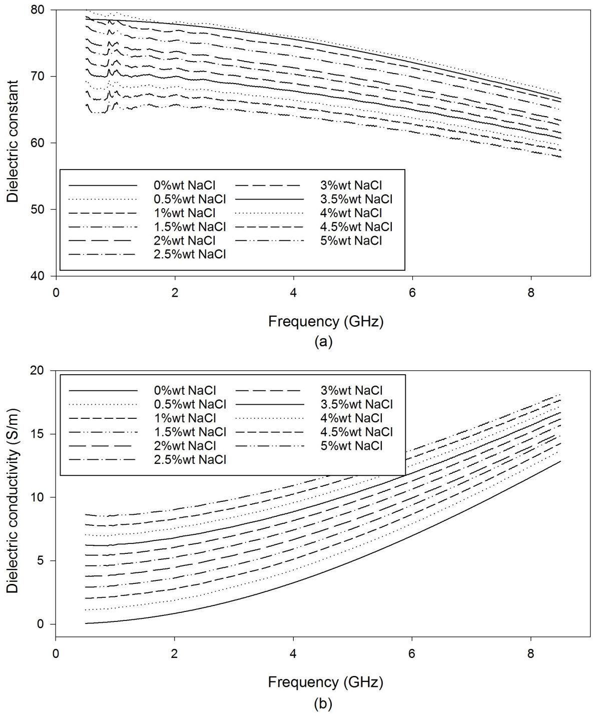

Fig. 2. Relative permittivity of water with 0%wt sucrose with different weight concentrations of NaCl: a) Dielectric constant b) Dielectric conductivity.

Furthermore, as observed in fig. 2a, the addition of salt does not affect the reduction pattern of the dielectric constant with frequency, so there is no change in the relaxation frequency. With regard to the dielectric conductivity, salt ions provide electrical conductivity to the solution. Free charges move the solution away from the ideal dielectric and turn into losses. The conductivity increases with the increment of sodium chloride, mainly at low frequencies (from 0.5 to 5 GHz). At high frequencies (above 5 GHz), free charges are not capable of following the fast field variations and their contribution disappear, remaining thus only water losses.

In fig. 3 and 4, the scans for 17%wt and 34%wt sucrose in water and varying salt concentrations are shown. Like in fig. 2, the behavior of salt is independent from the sucrose concentration, decreasing the dielectric constant and keeping its curve outline. The most relevant outcome of sucrose addition is the change of the decrease trend of the dielectric constant, which drops much faster with frequency than that of deionized water (fig. 2a). The addition of sugar brings a pronounced reduction of the dielectric constant, whose curve is turned around from a concave to a convex shape (fig. 5a).

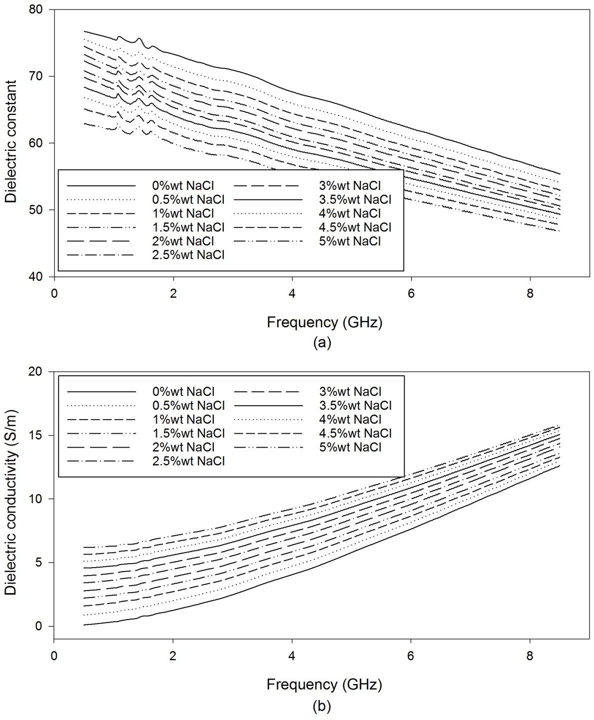

Fig. 3. Relative permittivity of water with 17%wt sucrose with different weight concentrations of NaCl: a) Dielectric constant b) Dielectric conductivity.

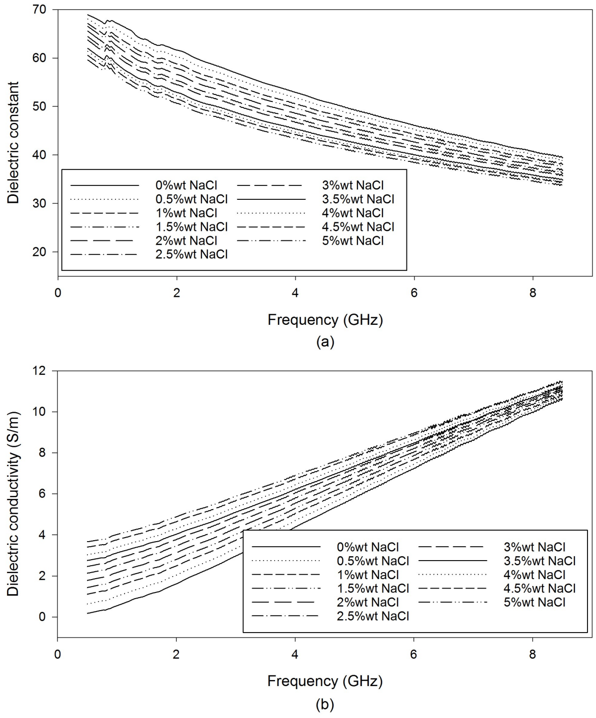

Fig. 4. Relative permittivity of water with 34%wt sucrose with different weight concentrations of NaCl: a) Dielectric constant b) Dielectric conductivity.

Last round of measurements was water with a 51%wt of sugar (fig. 5). In summary, salt increase the conductivity with little changes in the dielectric constant, whereas sugar decreases the dielectric constant without changing the losses.

However, what can be obtained with both compounds is more recommendable for narrow bands, where there is not a notable change for values of permittivity along frequency. This is because of the fact that sucrose moves backward the relaxation frequency and makes it difficult to get plain tendencies as human tissues do show in wide frequency bands [3]. Moreover, it is important to notice that the influence of salt on the dielectric conductivity is directly related to the relaxation frequency, from which all lines tend to converge to the same value regardless the salt concentration. The addition of salt is not an alternative to achieve a low dielectric constant because of the enormous losses that causes with small amounts, much higher than human tissues.

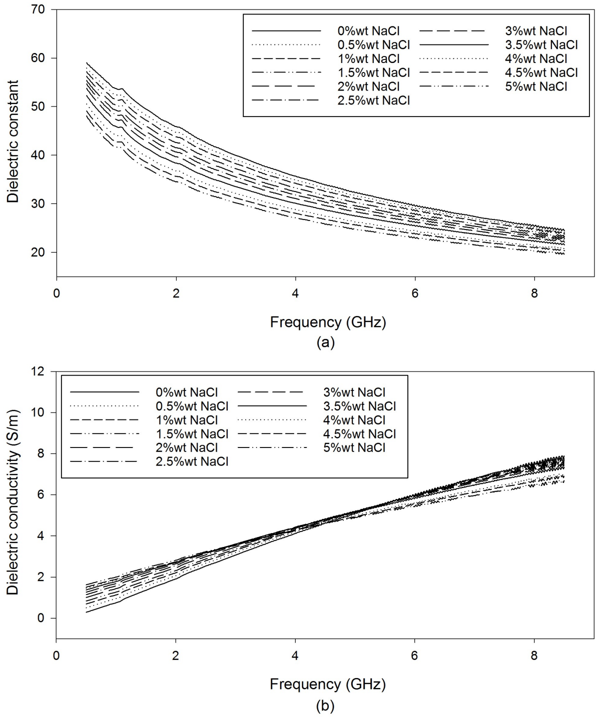

Fig. 5. Relative permittivity of water with 51%wt sucrose with different weight concentrations of NaCl: a) Dielectric constant b) Dielectric conductivity.

B. Cole-Cole fitting

From the previous results, a mathematical model can be obtained. For this purpose, every series are properly fitted to a single-pole Cole-Cole model as (3):

$$\varepsilon_r' - j\varepsilon_r'' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1+\left(j\omega\tau\right)^{1-\alpha}} + \frac{\sigma_s}{j\omega\varepsilon_0} \qquad (3)$$

where ε_∞ is the infinite dielectric constant, ε_s is the static dielectric constant, ω is the angular frequency in rad/s, τ is the relaxation time in s^{-1}, α is the exponential parameter and σ_s is the static conductivity in S/m. It is possible to fix the ε_∞ parameter to reference data from water's [17] to simplify the fitting, inasmuch as proper definition of this parameter is challenging. The remaining coefficients are obtained with the Levenberg–Marquardt algorithm and analyzed so a relation between their values and the mass fraction of sucrose and salt are parameterized as are depicted hereafter in table I.

TABLE I. COLE-COLE PARAMETERS OF THE SERIES OF SUGAR AND SALT

Parameter	**Fitting values according to the mass fraction of sucrose and salt**
ε_∞	5.89
$\Delta\varepsilon = \varepsilon_s - \varepsilon_\infty$	$(405.69 \cdot c_{Sucrose} - 307.09) \cdot c_{NaCl} - 27.405 \cdot c_{Sucrose} + 75.53$
τ(ps)	$(319525 \cdot c^3_{Sucrose} - 153143 \cdot c^2_{Sucrose} + 14467 \cdot c_{Sucrose} + 158.84) \cdot c^2_{NaCl}$ $+(753.53 \cdot c^2_{Sucrose} - 1.6545 \cdot c_{Sucrose} - 23.15) \cdot c_{NaCl} + 430.89 \cdot c^3_{Sucrose}$ $-136.86 \cdot c^2_{Sucrose} + 24.823 \cdot c_{Sucrose} + 8.2933$
α	$(81.587 \cdot c_{Sucrose} - 43.035) \cdot c^2_{NaCl} + (0.4214 \cdot c_{Sucrose}$ $+2.0407) \cdot c_{NaCl} - 0.6678 \cdot c^2_{Sucrose} + 0.9347 \cdot c_{Sucrose} - 0.0023$
σ_s(S/ m)	$(-280.71 \cdot c_{Sucrose} + 166.31) \cdot c_{NaCl} - 0.2855 \cdot c_{Sucrose} + 0.2547$

IV. PHANTOM FORMULATION

From the results of section III.A, a mathematical model in order to predict the required composition for a tissue of known dielectric properties was obtained. The dielectric constant and conductivity of tissues can be considered constant over narrow bands like ISM. Therefore, this model was deduced at 2.4 GHz.

Two mathematical relationships are necessary to describe the two parts of relative permittivity, so they were obtained separately. Firstly, an analysis of the dielectric constant's behavior was carried out by determining the influence of sucrose and sodium chloride on water solutions. For this purpose, the dielectric constant at 2.4 GHz is represented in fig. 6 for each fixed sucrose concentration varying salt concentrations.

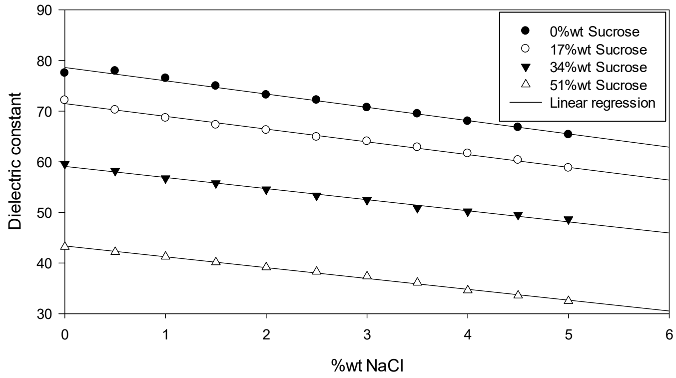

Fig. 6. Influence of sodium chloride on dielectric conductivity at 2.4 GHz in aqueous solutions of sucrose.

Values of dielectric constant show a linear behavior with the increment of salt concentration in all series, with a coefficient of determination of 98.95% in the worst case. Thus, we can consider the dielectric constant as a linear function with the following expression (4):

$$\varepsilon_r'(c_{NaCl}, c_{Sucrose}) = m_1(c_{Sucrose}) \cdot c_{NaCl} + b_1(c_{Sucrose}) \tag{4}$$

where m_1 is the slope and b_1 is the y-intercept, and both are dependent on the sucrose concentration. These parameters are determined in fig. 7 by analyzing their variation with respect to sucrose concentration from series of fig. 6.

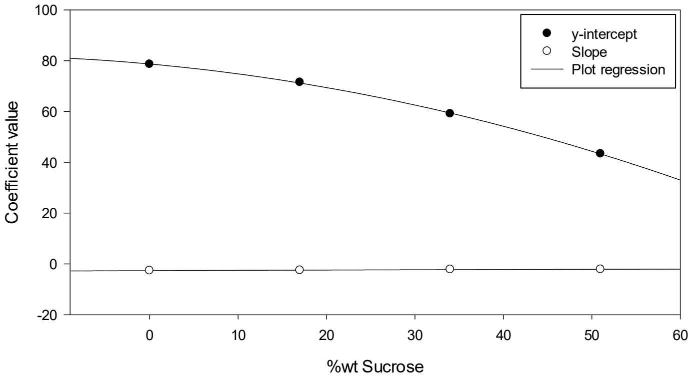

Fig. 7. Y-intercept and slope of series shown in Fig. 6 with respect to sucrose concentration.

In this case, the values for y-intercept can be fitted to a quadratic regression, with a coefficient of determination of 99.97%, and the slope can be fitted to a linear regression with a coefficient of determination of 92.44%. From those regressions, we get these new equations (5)(6):

$$m_1(c_{Sucrose}) = 0.01 \cdot c_{Sucrose} - 2.633 \tag{5}$$

$$b_1(c_{Sucrose}) = -0.007 \cdot c^2_{Sucrose} - 0.316 \cdot c_{Sucrose} + 78.704 \tag{6}$$

which are substituted in (4) as follows in (7):

$$\begin{aligned} \varepsilon_r'(c_{NaCl}, c_{Sucrose}) &= (0.01 \cdot c_{Sucrose} - 2.633) \cdot c_{NaCl} \\ &-0.007 \cdot c^2_{Sucrose} - 0.316 \cdot c_{Sucrose} + 78.704 \end{aligned} \tag{7}$$

where ε_r' is the dielectric constant, c_{NaCl} is the concentration of sodium chloride (mass percentage), and $c_{Sucrose}$ is the concentration of sodium chloride (mass percentage). The dielectric conductivity, which is directly related to the imaginary part of the relative permittivity by (2), is defined in a similar way. This parameter is represented in fig. 8 for each sucrose series.

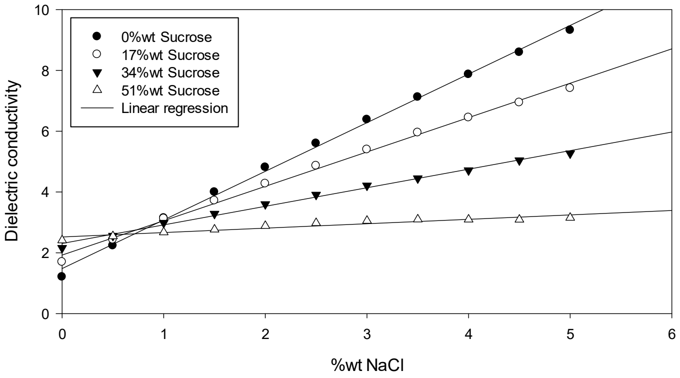

Fig. 8. Influence of sodium chloride on dielectric conductivity at 2.4 GHz in aqueous solutions of sucrose.

The values are fitted to a linear regression, with a coefficient of determination of at least 90.7%. As above, the behavior of the dielectric conductivity can be approximated to a linear equation as in (4), with its slope and y-intercept. They are also analyzed in terms of the sucrose concentration in order to find out how they change, as shown in fig. 9.

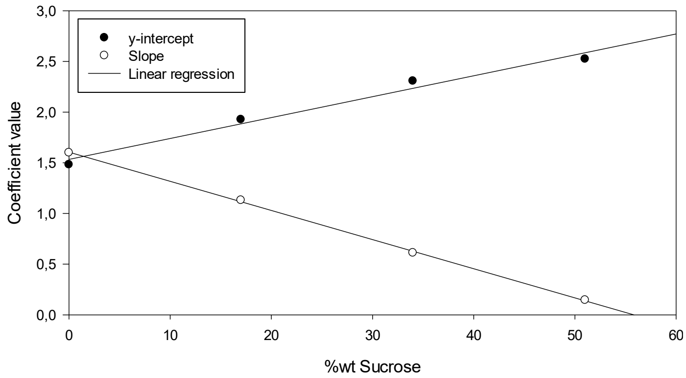

Fig. 9. Y-intercept and slope of series shown in Fig. 8 with respect to sucrose concentration.

Just as in the relations for the dielectric constant, the values of y-intercept and slope can be fitted to a linear regression with a coefficient of determination of 99.9% for the slope, and a 97.8% for the y-intercept fit. The two equations obtained as result of these fittings are (8)(9):

$$m_2(c_{Sucrose}) = -0.029 \cdot c_{Sucrose} + 1.604 \tag{8}$$

$$b_2(c_{Sucrose}) = 0.021 \cdot c_{Sucrose} + 1.533 \tag{9}$$

Next, the general formula is achieved by substituting these functions in the same way as before, taking into account that the slope equation had to be multiplied by the salt concentration in order to take into account the contribution of both compounds. Equation (10) is achieved as a result of this combination:

$$\begin{aligned}\sigma_d\left(c_{NaCl}, c_{Sucrose}\right) &= (-0.029 \cdot c_{Sucrose} + 1.604) \cdot c_{NaCl} \\ &+ 0.021 \cdot c_{Sucrose} + 1.533\end{aligned} \tag{10}$$

With the help of equations (7) and (10), the dielectric constant and conductivity can be predicted for any pair of sucrose and sodium chloride concentrations in water. Conversely, setting the desired values of dielectric parameters allows one to obtain the chemical formulation of the aqueous solution to achieve their phantoms. As an example, table II shows the properties of some achieved phantoms, along with those of human tissues reported by Gabriel [3]. The best achieved phantom is the heart one, with a deviation of less than two units in the dielectric constant despite using only simple compounds.

TABLE II. SYNTHESIZED PHANTOMS WITH RESPECT TO BODY TISSUES [3]

Tissue	**Phantom**	**Dielectric constant**		**Conductivity (S/m)**	
		Gabriel	**Phantom**	**Gabriel**	**Phantom**
Heart	39.2% Sucrose, 0% NaCl	54.92	53.13	2.22	2.26
Muscle	41.53% Sucrose, 0% NaCl	52.79	50.97	1.71	2.29
Pancreas	36.52% Sucrose, 0% NaCl	57.27	55.59	1.93	2.27
Liver	51.16% Sucrose, 0% NaCl	43.12	38.39	1.65	2.25
Colon	40.25% sucrose, 0% NaCl	53.97	52.59	2.00	2.30

V. CONCLUSION

In this work, a model to prepare custom-made phantoms of water with sugar and salt within the 2.4 GHz ISM band is provided. For this purpose, a campaign of dielectric broadband measurements of these solutions was fitted to a Cole-Cole model with the aim of predicting the permittivity from their composition. Then, two particular equations were deduced for the 2.4 GHz ISM band in order to achieve tailored phantoms since such frequency band is widely used for biomedical applications. From these formulas, recipes for phantoms of different body tissues at 2.4 GHz are given.

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