Temperature Dependent Dielectric Properties of Tissue Mimicking Phantom Material in the Microwave Frequency Range

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Abstract — **Microwave sensing represents a promising approach for non-invasive tissue temperature monitoring during hyperthermia treatment. Tissue mimicking phantom materials with corresponding dielectric properties and suitable for heating experiments are essential for preliminary methodical investigations as well as for the development of the measurement hardware.**

In the present paper, a fat tissue mimicking phantom material is investigated depending on the temperature in the range between 30 °C and 50 °C and the frequency range between 0.5 GHz and 7 GHz. The measured data are modeled by means of a two-pole Cole-Cole model and the temperature dependence of the Cole-Cole parameters is fitted by means of a second-order polynomial. The results show that this material imitate the dielectric properties of real fat tissue as well as its very low temperature dependence appropriately and can be used for practical experiments.

Index Terms — **tissue mimicking material, dielectric spectroscopy, temperature dependent dielectric properties, ultra-wideband.**

I. INTRODUCTION

Nowadays heat therapy or thermotherapy is widely used for different medical applications. Generally, thermotherapy can be divided by temperature range to three approaches: diathermia (temperature increase by 1-3 °C, can help in treating neuralgia, muscle spasms and other physiotherapy applications by increasing blood flow), hyperthermia (temperature increase by 4-8 °C, is used as support therapy in cancer treatment) and thermal ablation (temperature increase by 20-30 °C, destroys tissues, can be used instead of open surgery in oncology) [1]. Hyperthermia therapy is of great interest for more than fifty years. In combination with radiotherapy or chemotherapy hyperthermia can noticeably improve clinical outcome of cancer therapy [2].

But even today one of the most challenging scientific tasks in this research area is temperature monitoring. During hyperthermia procedure temperature increase should be quite low (until 44 °C), in order to prevent damage of healthy cells. For this reason, highly accurate temperature control is needed. The most spread way of temperature measurement is implementation of fiber optic catheters [3], which is painful, invasive and provide temperature value just from one point. In case that hyperthermia session duration is around 40-60 minutes and session should be repeated every week for a month or even more, invasive catheters are not the best option. A good alternative can be microwave temperature monitoring, which is painless, non-invasive and can give information about temperature from the whole area of interest.

Dielectric properties of biological tissues are playing the key role in microwave temperature monitoring. Because of its temperature dependence in general, their values change with ongoing hyperthermia treatment and, therefore, changes the electromagnetic scattering behavior of the illuminated tissue region in the microwave frequency range. This differential signal information has to be analyzed in order to estimate tissue temperature changes inside the human body. Even small changes of relative permittivity (ε) and effective conductivity (σ) can be detected by ultra-wideband (UWB) technology [1].

In principle, all human tissues can be divided into low water content (fat, bones, lungs) and high water content tissues (muscles, liver, blood). Due to the water content in the tissue, relative permittivity is decreasing with increasing temperature. The amount of water in tissue significantly affects temperature dependency of tissue. Thereby, measuring of temperature changes in low water content tissues needs more accuracy. This feature set a goal to archive reliable temperature dependent dielectric property values in microwave frequency range.

One of the opportunities to take experiments devoted to temperature change estimation is use of phantoms made of tissue mimicking materials (TMM). Since it is possible to define and control mechanic, geometrical and dielectric properties of TMM, they can be used for comparison with mathematically simulated models with specified properties, for testing of measurement systems or conducting repeatable measurements.

The purpose of this paper is to determine the temperature dependency of the dielectric properties of a fat TMM introduced in [4]. Due to its melting temperature above 50 °C, this material is appropriate for ex vivo heating measurements. These experiments on realistic phantoms are important for temperature estimation analysis. Results of this investigation allows us to get closer to the problem of developing a device for hyperthermia treatment monitoring.

II. MATERIAL AND METHODS

A. Tissue mimicking phantom

For preliminary investigations it is important to build simple phantoms with realistic dielectric contrast between simulated malignant and healthy tissues. For this purpose, as first step, phantoms made of only tumor and fat mimicking tissues can be used. Tumor tissue is a high water content tissue whereas fat is a low water content tissue. A large variety of phantom materials for both tissue types is widely used for measurements in microwave frequency range, but the number of materials which can be used for heating measurements is not that big.

Here, a study of fat TMM was conducted. Main requirements for a fat TMM are: dielectric properties comparable with human fat tissues including their temperature dependency, non-toxicity, time stability, heating ability, easy preparation, stable mechanical properties.

Table 1 presents results of a literature survey of low water content materials and mixtures. One of the attractive options can be an oil-gelatin phantom, because of similarity to human tissue dielectric properties, non-toxicity and easy preparation. But, unfortunately, gelatin starts melting at temperature around 35 °C [5], so it is impossible to use it for heating measurements. Another option can be 3D printed phantoms. They are made of acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA) and then can be filled with material with suitable dielectric properties. They fulfill most part of requirements, but in comparison with other TMMs they do not have required plasticity. Also, temperature dependent measurements can be held on animal tissues [6], because their dielectric and mechanical properties correspond to human tissue properties. But animal tissues cannot be used again after one heating experiment.

This paper describes a fat TMM prepared due to the recipe developed by research group from The Utrecht Department of Radiotherapy and the Lund Department of Radiation Physics [4]. This material is non-toxic, easy to prepare, consists of simple ingredients and well imitates low water content tissue at microwave frequencies. To obtain low value of relative permittivity it is needed to avoid high percentage of water in the phantom. Thus, the ingredients of this fat TMM include: flour, oil and saline (0.9 % NaCl per l) in proportion 500:225:25. Saline is used to manipulate conductivity. Oil allows the fat TMM to be moist and not to fall apart. Its preparation procedure is as follows. Firstly, flour should be sifted to avoid clots, then oil and saline should be gradually added. It is important to mix the ingredients constantly until the material will have a homogeneous structure. The ready-made fat TMM should be covered with paper tissue and plastic foil and stored in the fridge. This TMM is mechanically semisolid and plastic (can be used for any geometries of the phantom). Its storage time is up to several weeks.

TABLE I. Mimicking materials for low water content tissues.

Material	*Description*	*Temp. stable*	*Time stable*	*Easy to prepare*	*Ref.*
Gelatin based	hold shape, control of dielectric properties	-	-	+	[7], [8]
Oil, Vaseline based	hydrophobic viscous liquid or cream, non-toxic	+	-	+	[7] - [10]
Honey	syrup, non-toxic	-	+	+	[4], [8], [11]
Flour based	safe, non-toxic, control of viscosity	+	+	+	[4], [9]
Acrylamide	increasing mechanical strength	+	-	+	[8], [11], [12]
ABS/PLA	plastic, production of forms or containers	+	+	+	[6], [7]
Animal fat	properties and structure are quite similar to human tissue	+	-	+	[6]

B. Temperature dependent dielectric properties

The temperature dependent dielectric properties are described by the complex relative permittivity ($\underline{\varepsilon}$) and the effective conductivity (σ)

$$\begin{aligned} \underline{\varepsilon}(\omega,\vartheta) &= \varepsilon'(\omega,\vartheta) - i\varepsilon''(\omega,\vartheta) \\ \sigma(\omega,\vartheta) &= \omega\varepsilon_0\varepsilon''(\omega,\vartheta) \end{aligned} \qquad (1)$$

where the real part ε' represents the relative permittivity, the imaginary part ε'' the relative dielectric loss, ε_0 the permittivity of free space, $\omega = 2\pi f$ the angular frequency and ϑ the temperature.

C. Measurement setup

The temperature dependent dielectric properties of the fat TMM were measured by dielectric spectroscopy method in the frequency range of 0.5 GHz to 7 GHz and in the temperature range between 30 °C and 50 °C. The scheme of the measurement setup is presented at Fig. 1. and in the photo at Fig. 2.

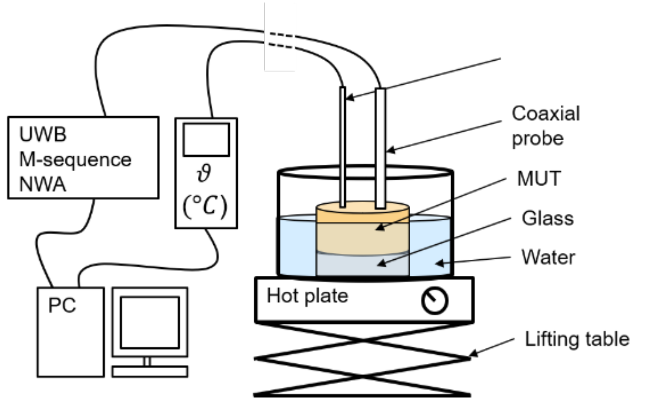

Figure 1. The scheme of the measurement setup for temperature dependent ultra-wideband dielectric spectroscopy.

The measurement setup includes UWB M-sequence network analyzer (NWA), (the detailed description of this technology is given in [13], [14]), open-ended coaxial probe (N1501A performance probe, Keysight Technologies, Santa Clara, CA, USA), temperature probe, high precision thermometer (GMH 3750, GHM Messtechnik GmbH, Remscheid, Germany), material under test (MUT), hot plate, lifting table, three glass tanks and measurement software. Small glass tank of cylindrical shape with a diameter of 5 cm and a height of 3 cm was filled with examined MUT (fat TMM). It was placed on another glass tank to avoid disturbing reflections from the metallic hotplate during the measurement as is proved by several research groups [15], [16], as well as in our own experiments. As it is shown at Fig. 2, the performance probe connected to the NWA and the temperature probe connected to the thermometer were placed in direct contact with the MUT. The vertical position of the MUT and thus, the contact pressure of the probes onto the MUT, were regularized by a lifting table. The heating was achieved by a hot plate via a water bath and controlled by a thermometer during the whole procedure.

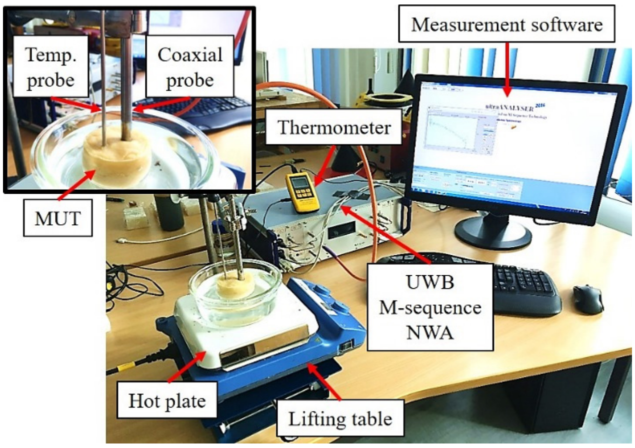

Figure 2. Laboratory measurement setup for tissue analysis.

D. Measurement procedure

In a first step, calibration of the probe was carried out based on OSM (open, short, match) technique, where distilled water was used as matching liquid. After calibration, dielectric properties of the MUT were measured ten times at constant temperature with time interval of five minutes. This experiment was held to verify a non-linear time dependent effect mentioned in [6], when dielectric properties were increasing with time after positioning of the probe. This effect did not occur for the fat TMM under study. Relative permittivity and effective conductivity of the fat TMM sample as a function of frequency at a constant temperature over a time period of 45 minutes did not show a clear increasing trend.

In a next step, temperature dependent measurements were carried out in the range between 30 °C and 50 °C with step of 1 °C. This experiment was repeated eight times to achieve reliable results. Fig. 3 shows averaged relative permittivity and effective conductivity of the fat TMM during the heating cycle for these measurements.

III. RESULTS

From analysis of the data presented below, we can see that the values of relative permittivity and effective conductivity of the MUT correlate well with literature data [6], [17], [18]. Permittivity is within the range between 3 and 7, conductivity between 0.02 and 0.5 S/m. Also, we can conclude that, as expected, temperature dependency of fat TMM is very low. This effect can be explained by small amount of water in material (approximately 3.3 %).

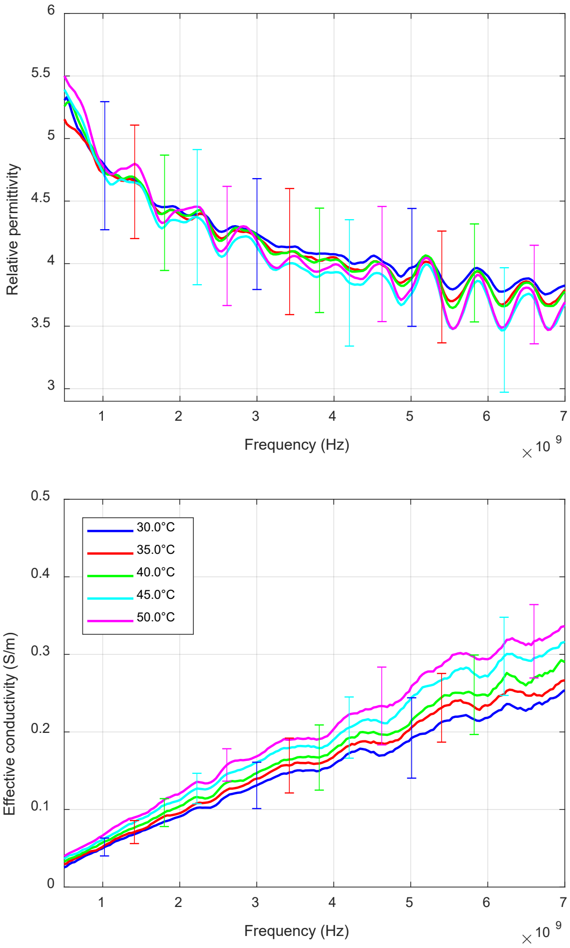

Figure 3. Mean relative permittivity (above) and mean effective conductivity (below) of eight fat TMM samples as a function of frequency at different temperatures. The error bars indicate the corresponding standard deviation.

A fitting procedure, described in [6], was applied in order to compare the results of the studied fat TMM with other materials used to mimic low water content tissues. This fitting procedure provides temperature dependent Cole-Cole parameters. A two-pole Cole-Cole model was used, so that fitted temperature dependent dielectric properties can be computed due to (2)

$$\begin{aligned} \varepsilon_{fit}(\omega,\vartheta) &= \varepsilon'_{fit}(\omega,\vartheta) - i\varepsilon''_{fit}(\omega,\vartheta) \\ &= \varepsilon_{\infty,fit}(\vartheta) + \sum_{k=1}^{2} \frac{\Delta\varepsilon_{k,fit}(\vartheta)}{1+(i\omega\tau_{k,fit}(\vartheta))^{1-\alpha_k}} + \frac{\sigma_{s,fit}(\vartheta)}{i\omega\varepsilon_0} \end{aligned} \tag{2}$$

where ε'_{fit} represents the relative permittivity, ε''_{fit} the relative dielectric loss, $\varepsilon_{\infty,\mathrm{fit}}$ represents the permittivity at very high frequencies, $\Delta\varepsilon_{1,2,fit}$ are the dispersion amplitudes, $\tau_{1,2,\,fit}$ are the corresponding relaxation times and $\sigma_{s,\,fit}$ *is* the static conductivity.

The temperature dependent Cole-Cole parameters are given by second order polynomial (3) with coefficients A_n, B_n and C_n (n = 1…6), which are presented in Table 2. The parameters $\alpha_{1,2}$ are set to 0.4 and represent empirical distribution parameters describing the broadening of the dispersion.

$$\begin{aligned} \varepsilon_{\infty,fit}(\vartheta) &= A_1\vartheta^2 + B_1\vartheta + C_1 \\ \Delta\varepsilon_{1,fit}(\vartheta) &= A_2\vartheta^2 + B_2\vartheta + C_2 \\ \tau_{1,fit}(\vartheta) &= A_3\vartheta^2 + B_3\vartheta + C_3 \\ \Delta\varepsilon_{2,fit}(\vartheta) &= A_4\vartheta^2 + B_4\vartheta + C_4 \\ \tau_{2,fit}(\vartheta) &= A_5\vartheta^2 + B_5\vartheta + C_5 \\ \sigma_{s,fit}(\vartheta) &= A_6\vartheta^2 + B_6\vartheta + C_6 \end{aligned} \tag{3}$$

TABLE II. Temperature coefficients of the second order polynomial fit to the temperature dependent Cole-Cole parameters of fat TMM.

	n	A_n	B_n	C_n
$\varepsilon_{\infty,fit}$	1	-0.219·10^{-3} (K^{-2})	0.016 (K^{-1})	1.659
$\Delta\varepsilon_{1,fit}$	2	-0.069·10^{-3} (K^{-2})	0.002 (K^{-1})	2.430
$\tau_{1,\,fit}$	3	-0.154 (fs·K^{-2})	0.335 (ps·K^{-1})	-1.327 (ps)
$\Delta\varepsilon_{2,fit}$	4	-0.014·10^{-3} (K^{-2})	0.002 (K^{-2})	14.95
$\tau_{2,\,fit}$	5	-0.016 (ns· K^{-2})	1.093 (ns·K^{-2})	-6.553 (ns)
$\sigma_{s,\,fit}$	6	-0.030 (mS·K^{-2})	2.627 (mS·K^{-2})	-66.84 (mS)

The curves of the relative permittivity and effective conductivity determined by the two-pole Cole-Cole model for studied temperature range in step of 5 °C are presented at Fig. 4. The relative permittivity decreases slightly with increasing temperature after an intersection point at around 1.5 GHz. The effective conductivity shows monotonic temperature dependency in the whole studied frequency range, where the conductivity is increasing with increasing temperature.

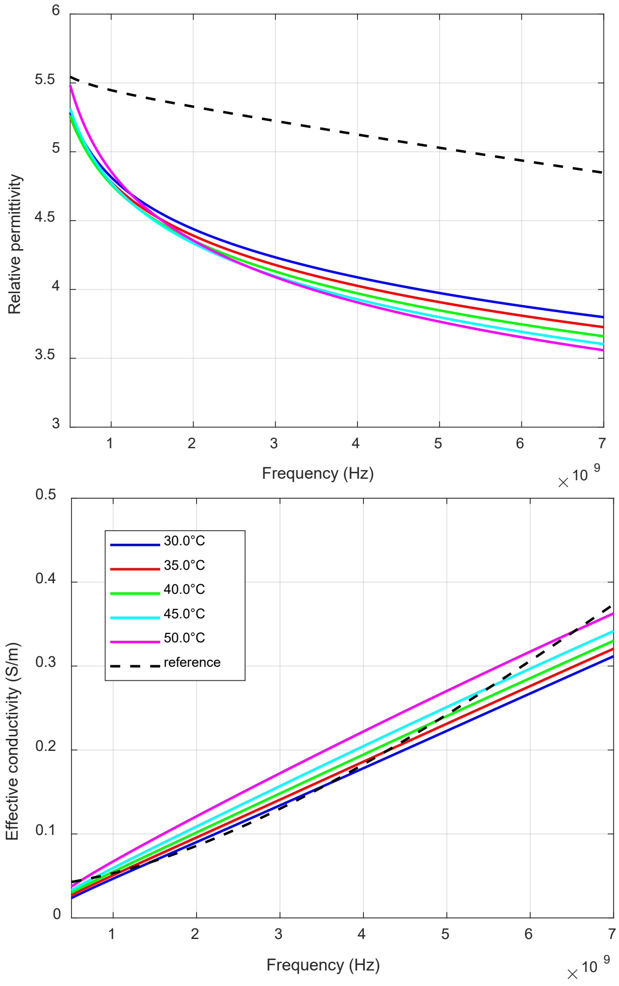

Figure 4. Relative permittivity (above) and effective conductivity (below) of fat TMM as a function of frequency at different temperatures. Black curves show the dielectric properties of fat reported by Gabriel [17] at 37 °C.

The difference between the measured data and the results after fitting procedure was computed by

$$\begin{aligned} \delta\varepsilon'_{measured,fit}(\omega,\vartheta) &= \varepsilon'_{measured}(\omega,\vartheta) - \varepsilon'_{fit}(\omega,\vartheta) \\ \delta\sigma_{measured,fit}(\omega,\vartheta) &= \sigma_{measured}(\omega,\vartheta) - \sigma_{fit}(\omega,\vartheta) \end{aligned} \tag{4}$$

with $\sigma_{fit}(\omega,\theta) = \omega\varepsilon_0\varepsilon''_{fit}(\omega,\theta)$.

Fig. 5 shows the difference of relative permittivity and effective conductivity of fat TMM between experimental and modelled data. The deviations are around 0.3 for the relative permittivity and less than 0.1 S/m for the effective conductivity. Especially, the conductivity fits model the measured data very exactly. However, the differences between measured and fitted data are slightly higher than in our previous study [6] (0.1 and 0.05 S/m respectively). Thus, based on ongoing measurements we plan to further increase the measuring accuracy.

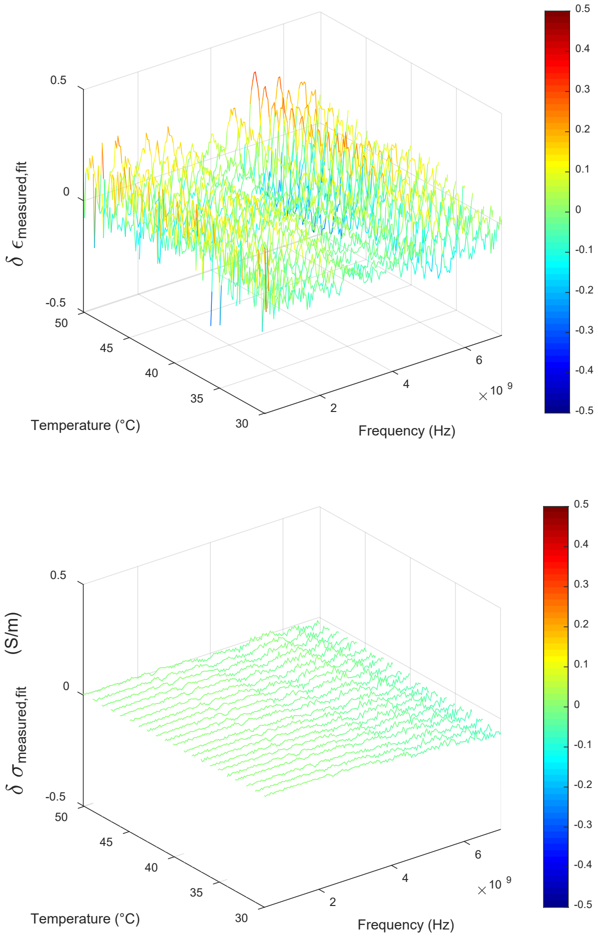

Figure 5. Difference between the measured data and the temperature dependent two pole Cole-Cole model of relative permittivity (above) and effective conductivity (below) of fat TMM.

IV. CONCLUSIONS

In this paper we presented a study of a fat tissue mimicking material which can be used for temperature estimation measurements based on microwaves. We investigated via dielectric spectroscopy method the temperature dependent dielectric properties in the temperature range between 30 °C and 50 °C and in the frequency range from 0.5 GHz up to 7 GHz. Furthermore, we applied a fitting procedure to describe the frequency and temperature dependency of the dielectric properties in the specified ranges to compare our results with other TMM or animal fat tissue studies [6].

The measurements showed that the examined material possess suitable properties for simulation of human fat tissue in microwave frequency range. It well imitates not only dielectric properties, but also their temperature independency. Because of its mechanical and dielectric properties this TMM meets the specified requirements for the heating experiments, too. The results of this study can be used for the experimental measurements via UWB technology for non-invasive temperature monitoring during hyperthermia therapy.

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