Advanced Temperature Dielectric Spectroscopy of Muscle Phantom at Microwave Frequencies

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Abstract — The temperature dependency of the dielectric properties of tissues is very important for the development of novel microwave systems intended for non-invasive temperature monitoring. This paper deals with the measurement and optimization of the temperature dependence of the dielectric parameters of a muscle tissue mimicking phantom. The measurements were performed in the frequency band 0.1 – 3 GHz and in the temperature range 25 – 45 °C. The differences in the dielectric parameters caused by temperature change were analyzed and compared with the reference.

Index Terms—temperature dependent spectroscopy, muscle phantom, tissue mimicking phantom, UWB radar, hyperthermia.

I. INTRODUCTION

The electromagnetic waves are useful in many medical applications. Growing interest in using electromagnetic energy at microwave frequencies for medical imaging, tumor detection, and tumor therapies, calls for various tissue-mimicking phantoms. The major advantage of electromagnetic waves is their non-ionizing character. The dielectric parameters determine, how the electromagnetic wave interacts with the medium under test (MUT). Our work is focused on developing tissue mimicking phantom, which will be representing frequency and temperature dependence of dielectric parameters of human muscle.

The knowledge of temperature dependence of dielectric parameters of human tissues is essential for the development, testing and calibration of any microwave system which will be able to monitor non-invasively the temperature within the human body during thermotherapy (e.g. hyperthermia). In our previous work we presented the possibility to measure small changes caused by local heating by means of UWB M-sequence radar [1]-[2]. Hyperthermia treatment is non-toxic treatment without side effects [2]. The main goal of the hyperthermia treatment is to increase the temperature of the tumors of 4 – 8 °C [2]. The effectiveness of microwave hyperthermia in the treatment of the tumors is reported in the several phase III clinical trials e.g. in [3]-[4].

The non-invasive temperature measurement via UWB radar is based on the assumption that dielectric properties (relative permittivity and effective conductivity) of human tissues are temperature dependent [1]. The approach is based on the recording of backscattered signals UWB from the heated region. As far as we know there are only few publications dealing with this topic in the microwave frequency range. Lazebnik et. al. [5] presented the temperature (20 - 60 °C) dependent measurement of the dielectric properties of the porcine liver in the frequency range 0.5 – 20 GHz. In [6] the study on the variation of dielectric properties of gray matter with temperature up to 60 °C is presented. Ley et. al. [7] published the study on the temperature dielectric spectroscopy of four biological tissues. Temperature dependent dielectric properties of blood, liver, muscle and fat were measured by using open-ended coaxial probe in the frequency range 0.5 GHz – 7 GHz and in the temperature range between 30 – 50 °C. The measured data were fitted by temperature dependent two-pole Cole-Cole model. According to the study from Ley the strongest temperature induced change of the relative permittivity occurs between 1 – 4 GHz [7]. The temperature dependence was evaluated up to 3 GHz. The aim was to get as close as possible to the muscle temperature dependence.

II. MATERIALS AND METHODS

A. Temperature dependent reference model

We adopted the temperature dependent two-pole Cole-Cole model by Ley et al. [7] as the reference. This model was derived from the dielectric spectroscopy performed in the temperature range 30 – 50 °C. The temperature dependent complex permittivity can be described according to the following equation:

\[ \varepsilon(f, \vartheta) = \varepsilon'(f, \vartheta) - j\varepsilon''(f, \vartheta) \]  \hspace{1cm} (1)

where \( \varepsilon \) is the complex permittivity, \( \varepsilon' \) is the relative permittivity, \( \varepsilon'' \) represents the dielectric loss, \( f \) is frequency and \( \vartheta \) is temperature. The effective conductivity \( \sigma \) is calculated as follows

\[ \sigma(f, \vartheta) = 2\pi f \varepsilon_0 \varepsilon''(f, \vartheta) \]  \hspace{1cm} (2)

where \( \varepsilon_0 \) is permittivity of the free space.

B. Measurement setup

For the temperature dependent dielectric spectroscopy, the procedure proposed in [7] was used. The measurement was
The measurement is based on the one port reflection measurement \( (S_{11}) \). Three term calibration (open, short and unmatched load of known characteristic) was performed before each measurement at room temperature 20 °C. As the matching liquid the 0.1 (mol\(^{-1}\)) saline solution was used.

For the temperature dependent spectroscopy, the dielectric probe DAK – 12 (SPEAG company, Switzerland) which is able to measure in the frequency range 0.1 – 3 GHz was used. The probe was connected by coaxial cable to the handheld Keysight N9913A Field Fox VNA. The tissue mimicking phantom was immersed into the water bath in the polyethylene bag to avoid the contact between water and phantom. The dielectric probe was attached to the tissue mimicking phantom with the decent pressures. The water in the container was not in the contact with the dielectric probe. The water bath was placed on the lifting cart to ensure the constant contact between MUT and probe. The water in the bath was tempered to the required temperature of the MUT and measurement. For the temperature monitoring of the phantom, the temperature probe was inserted in the phantom in the depth 15 mm under the phantom surface (as illustrated in the Fig. 1). The measurement was performed with the step 5 °C in the temperature range 25 – 45 °C. The whole measurement setup can be seen in the Fig. 1. Each measurement was repeated ten times for each phantom version.

**C. Temperature dependent tissue mimicking phantom**

Muscle mimicking phantom previously presented in [9] was adjusted to meet dielectric properties in the temperature range 25 °C – 45 °C. Muscle tissue contains high percentage of water. In order to achieve the same properties, it was mainly adjusted by the proportion of distilled water along with the proportion of PE powder. No preservative was used since it is not possible to use the phantom after warming up. The composition of phantom was gradually changed. Version 1 and 2 differ in the volume of distilled water. Version 3 and 4 contain less PE powder and higher percentage of distilled water. Version 4 consists of 84 % of distilled water and also 3.2 % of TX-151 which ensures good mixing of the agar solution and PE powder as well as phantom’s mechanical properties. The percentage of substances is summarized in Table I. Preparation procedure is described in [8]. Vacuum system was used for eliminating the air bubbles. Each fabricated phantom was of cylindrical shape with height of 60 mm and diameter of 120 mm. To warm up the phantom uniformly by 5 °C takes more than 1 hour due to the relatively low temperature conductivity of the phantom.

**D. Dielectric parameter evaluation**

As it is described above, four versions of the phantom were prepared and measured. The measured temperature dependency of the dielectric parameters of the phantom was compared according to the following workflow. The important parameter was the difference in the relative permittivity and effective conductivity between each temperature through the whole frequency band. We choose frequency band \( fs = 1 - 2.5 \) GHz. At these frequencies the temperature dependent difference of the relative permittivity \( \Delta \varepsilon' \) and effective conductivity \( \Delta \sigma \) were determined. It was calculated according to the following equations:

\[
\Delta \varepsilon'(fs, \Delta \theta) = \text{abs} \left( \varepsilon'(fs, \theta + 5^\circ C) - \varepsilon'(fs, \theta) \right) \tag{3}
\]

\[
\Delta \sigma(fs, \Delta \theta) = \text{abs} \left( \sigma(fs, \theta + 5^\circ C) - \sigma(fs, \theta) \right) \tag{4}
\]

where \( \Delta \varepsilon' \) is the absolute difference of permittivity between two phantom temperature and \( fs \) are the selected frequencies. Analogically \( \Delta \sigma \) is the difference of effective conductivity between two temperature. The average value of the difference in the dielectric parameters was calculated from differences gained at frequencies \( fs \). These differences were compared with Ley et. al. as shown the Fig. 2.

The second parameter which was used for the comparison between our measurements and reference were the temperature coefficients calculated according to the following equations [10]:

\[
\frac{\Delta \varepsilon'}{\varepsilon'} \text{ and } \frac{\Delta \sigma}{\sigma} \text{ in } \% \text{ C}^{-1} \tag{5}
\]

**III. RESULTS**

We investigated the change of the dielectric properties during the heating of four fabricated phantoms. As the next
The absolute difference of dielectric parameters were calculated (according to eq. (3) and (4)). In the Fig. 2 (a) and (b) the differences are plotted averaged over frequencies $f_s$ for all measured phantoms. The first blue columns are the differences of the reference from Ley. The absolute change of the relative permittivity is about 0.6 per 5 °C. Regarding the effective conductivity the change is approximately 0.3 (S/m). The smaller difference deviation from the reference (blue column), the better phantom is it. The lowest difference in the relative permittivity has version 4.

The Fig. 3 (a) and (b) show the temperature and frequency dependent dielectric parameters of the muscle phantom dielectric parameters – full lines (phantom version 4) compared to the reference from Ley (dashed lines) in the temperature range 25 – 45 °C (five curves) with error bars. The error bars were calculated from ten repeated measurements. The relative permittivity decreases with the increasing temperature. The courses of the temperature dependence of the relative permittivity of the phantom in the frequency band 0.5 – 3 GHz. are in agreement with the temperature muscle model from Ley. Below this frequency the courses of the lines have different progress. This could be caused by the measurement technique.

In the Table II and III, the temperature coefficients are presented. From these tables it is also obvious that the lowest difference between measured data and model from Ley et. al. is in case of phantom version 4.

The effective conductivity (Fig. 3 (b)) of the measured phantom is very similar to the model from Ley under the frequency 500 MHz. Up to this frequency, the measured frequency dependence is rising more slowly than the model, however the difference at the higher frequencies is still in the

**Table II. Relative permittivity temperature coefficient at 1.5 GHz.**

| Temperature (°C) | 25  | 30  | 35  | 40  |
|------------------|-----|-----|-----|-----|
| Ley              | 1.14| 1.05| 0.97| 0.89|
| Version 1        | -2.11| -1.60| -1.68| -1.9|
| Version 2        | -0.22| -0.80| -1.2 | -0.96|
| Version 3        | -0.63| -1.22| -0.60| -1.17|
| Version 4        | -1.35| -1.02| -0.78| -0.82|

**Table III. Effective conductivity temperature coefficient at 1.5 GHz.**

| Temperature (°C) | 25  | 30  | 35  | 40  |
|------------------|-----|-----|-----|-----|
| Ley              | 0.67| 1.54| 2.28| 2.83|
| Version 1        | 0.74| 0.84| 1.9 | 3.11|
| Version 2        | 3.51| 3.43| 6.01| 0.621|
| Version 3        | 1.74| 1.54| 1.06| 7.06|
| Version 4        | 2.09| 2.01| 1.55| 2.73|

![Fig. 2. Comparison of an average absolute difference of relative permittivity (a) and effective conductivity (b) depending on the temperature change.](image)

![Fig. 3. Measured temperature dependence of tissue mimicking phantom (version 4) relative permittivity (a) and effective conductivity (b) with error bars – full lines compared to the temperature model of muscle from Ley – dashed lines.](image)
tolerance and acceptance. The effective conductivity of the phantom is increasing with the temperature to the frequency cross-over point (1.6 GHz). Up to this cross-over point, the effective conductivity is decreasing with the temperature.

I. CONCLUSIONS

In this paper, the measurement procedure of the temperature dependence of dielectric parameters was presented. Four versions of the muscle mimicking phantom composed from agar, PE powder, TX-151 and distilled water were fabricated and dielectric parameters were measured in the temperature range 25 – 45 °C in steps 5 °C. Due to the required temperature and frequency dependence of the phantom (with the muscle model from Ley) it was necessary to adapt the phantom composition.

The measured data were compared with the temperature dependent model of muscle tissue from Ley. The average difference of the dielectric parameters between two neighboring temperatures was observed and evaluated. The resulted phantom can be used for testing microwave imaging systems or hyperthermia applicators.

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