

Study of Dielectric Properties of Biological Tissues in the Microwave Frequency Range

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Abstract

The complex dielectric constants at room temperature of various goat tissues (liver, muscle, kidney, heart and brain) and corn syrup were measured in the frequency range 1 to 10 GHz with the help of a HP Network Analyzer N5230A. Open ended coaxial cable method was employed for the measurement. The system imperfections are completely avoided by calibrating the system with four known materials and their reflection coefficients were used in the calculation along with the reflection coefficient of the sample. The relaxation frequency in the δ region, spread of relaxation, volume fraction of protein present in tissues are calculated from the measured dielectric data. The dielectric constant of corn syrup samples suggests the feasibility of using corn syrup as a tissue equivalent for microwave imaging applications.

Introduction and Scope

Electrical properties of biological materials and their interaction with electromagnetic waves have attracted the attention of researchers working in the field of medicine and Electromagnetics. Studies indicate that microwaves have tremendous potential especially in the diagnostic and therapeutical medical applications. A number of innovative technologies employing radiowaves and microwaves are under investigation for the purpose of developing new techniques to improve detection, diagnosis and treatment of cancer. In order to understand the interaction of electromagnetic fields in tissues, it is important to know accurately its complex dielectric constant.

The published data in the literature shows a substantial contrast that exists between different types of tissues [4-7]. Even though some of the tissues electrical property is available in the microwave frequency range, it is not sufficient for its applications in medical field.

Therefore we conducted a study to measure the complex dielectric property of various goat tissues (invitro) in the frequency range 1GHz to 10GHz with the help of a HP Network Analyzer 8510B. The dielectric property of corn syrup also in various concentrations were calculated and compared with that of the tissues to study the feasibility of it being used as a tissue equivalent.

We adopted the open ended coaxial probe method to measure the dielectric properties since the coaxial probe technique does not require tissue manipulation or preparation. The end of the probe is simply placed in contact with the tissue sample and the complex input reflection coefficient is measured as a function of frequency using a vector network analyzer. The measured reflection coefficient is then converted to a complex permittivity using numerical models [10-15].

The present work is not only aimed at measuring the dielectric property information of various normal tissues, but to find out its more specific characteristics like relaxation frequency, spread of relaxation, volume fraction solid/water fraction in tissues, volume fraction of protein from this information.

Materials and Method

The dielectric constant measurement of biological samples at microwave frequencies is a difficult task. Different methods are reported for the accurate measurement of high loss samples. But most of the methods are suited only for a certain range of frequency [7]. In this work, we adopted the coaxial cable method, which can be used, for a wide range of frequencies with a single probe. Network analyzer HP8510B was used for the measurement. Theory of the technique is as follows.

The lumped element approach was selected for measuring the reflection, which is related to the characteristic impedance of the transmission line and that of the sensor probe. The impedance of the sensor is a function of the frequency and relative permittivity of the test sample. Under quasi-static approximation the stationary formula for the aperture admittance of an open-ended coaxial line terminated by a semi-infinite medium on a ground plane reduces to

$$Y_L = j \frac{2\omega I_1}{\ln \frac{b}{a}} \epsilon^* - j \frac{\omega^2 \mu I_2}{\left[\ln \frac{b}{a}\right]^2} \epsilon^{*2} + \frac{\pi \omega^4 \mu_0^{3/2} [b^2 - a^2]^{3/2}}{12 \left[\ln \frac{b}{a}\right]^2} \epsilon^* \quad \dots\dots\dots(1)$$

where a and b are the inner and outer radii of the coaxial cable respectively, μ is the complex permeability of the semi infinite medium, ω is the angular frequency of electromagnetic fields I_1, I_2 the two triple integrals dependent on the radii but constant otherwise [16].

The actual admittance of the aperture terminated by a sample from the measured reflection coefficient after calibrating the system with three standard materials as

$$\frac{Y_s - Y_1}{Y_c - Y_3} \times \frac{Y_3 - Y_2}{Y_1 - Y_2} = \frac{\partial s_1 \times \partial s_2}{\partial s_2 \times \partial s_3} \dots\dots\dots(2)$$

follows. Y_s is the desired aperture admittance terminated by the sample material, $Y_{1,2,3}$ are the aperture admittance in the standards respectively. By using the 4th standard and noting bilinear transformation characteristic of admittance, the aperture admittance can be written as

$$Y_L = \epsilon_r^* + A_0 \epsilon_r^{*2} + A_1 \epsilon_r^{*2.5} \dots\dots\dots(3)$$

ϵ_r^* is the complex permittivity of the material A_0 and A_1 are the constants dependent on the frequency and dimensions of the aperture. Generally the radiation from the coaxial aperture can be neglected at lower frequencies. Equations (2) and (3) are used to determine the complex permittivity of the sample assuming that the 3rd standard used is a short circuit. We used air, water, short circuit and methanol as standards.

Sample Preparation

- (1) Freshly sacrificed goat tissues were used for the experiment. We used liver, kidney, muscle, brain and heart. Experiments were repeated by using the tissues of different goats of same age and group. Before the measurement, tissues were treated in 0.9% saline solution and temperature kept at 30°C.
- (2) Corn syrup samples were prepared by carefully missing the corn flour in boiling 0.1N saline and continuously stirring till it forms a paste.

Experiment

The experimental set up is as shown in figure.1. The open ended coaxial probe was placed touching the tissue sample. The Network analyzer of Agilent N5230A was used to measure the reflection coefficient from the coaxial probe in the frequency range 1GHz to 10GHz. Care was taken that the height and diameter of the beaker must be larger than three wavelengths to get accurate results.

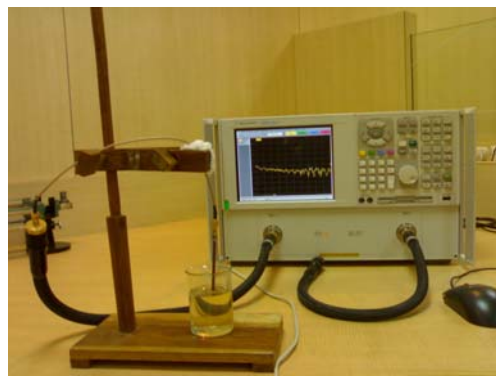


Figure 1: Experimental set up for measurement of S_{11} from the sample.

The experiment was conducted with different goat tissues and also with corn syrup samples.

Result and Discussions

The complex dielectric property information of 5 goat tissues were measured in the frequency range 1GHz to 10GHz. The experimental results are shown in Fig. 2 and Fig 3. We compared our results with some of the available data and found good agreement [17].

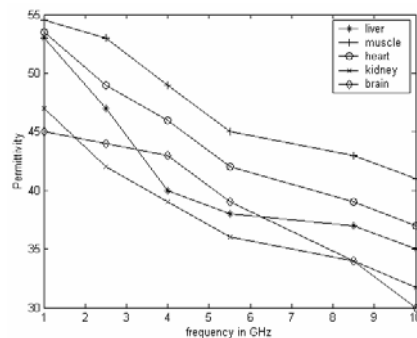


Figure 2: Permittivity as a function of frequency.

The result shows that tissues exhibit a continuous decrease in permittivity as frequency varies from lower to higher range with an associated increase in conductivity.

The dielectric permittivity values for the tissues which we measured in the frequency range 1GHz to 10GHz, show a

variation of 10 to 15. This could be partly due to the dipolar relaxation of water of hydration and partly from rotational relaxation of polar side chain and possibly also from ionic effects. From the dielectric data, it is identified that dispersion is in the δ region, suggest that the relaxation of molecules have activation energy of rotation between that of protein and free water.

It is seen from the Fig. 3 that the conductivity values in all cases increase with frequency. In tissues the dominant contribution to the conductivity at low frequencies are ionic conduction through the extra cellular and intra cellular fluids but above 100MHz conductivity resulting from dielectric loss becomes increasingly significant. At UHF and Microwave frequencies conductivity variation is mainly due to relaxation effects.

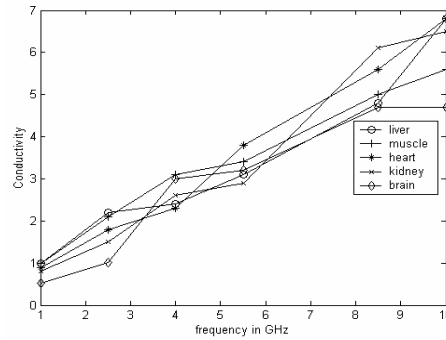


Figure 3: conductivity as a function of frequency.

The main possible relaxation mechanisms are i) Maxwell-Wagner process due to interfacial polarization of electrolyte and relatively non-conducting protein molecule [19]. ii) Dielectric loss of small polar molecules and polar side chains on proteins and iii) Dielectric relaxation of water [18].

Relaxation frequency f_s , the dielectric constant at low frequency ϵ_s and α the measure of spread of relation time were calculated from the measured ϵ' and ϵ'' data by using the equation derived from the cole-cole dielectric theory [19].

$$\frac{\lambda \epsilon''}{\epsilon' - \epsilon_\alpha} = \lambda \left[\frac{\lambda_s}{\lambda} \right]^{1-\alpha} \left[1 - \left(\frac{\lambda_s}{\lambda} \right)^{1-\alpha} \frac{\alpha \pi}{2} \right]. \tag{4}$$

$$\epsilon^* = \epsilon_\alpha + \frac{\epsilon_s - \epsilon_\alpha}{1 + j \left[\frac{\lambda_s}{\lambda} \right]^{1-\alpha}}. \tag{5}$$

Table I: Dispersion Parameters of Different Biological Tissues.

Tissues	f_s MHz	α
Liver	98	0.077
Muscle	135	0.045
Heart	141	0.053
Kidney	90	0.080
Brain	67	0.10

Dispersion parameters shown in table I indicate that this can be used for studying the behavior of different tissues.

Table II: Volume Fraction of Solid Content in Biological Tissues.

Tissue	Solid content
Liver	0.33
Kidney	0.39
Muscle	0.34
Heart	0.28
Brain	0.41

We calculated the water fraction of the tissues from the measured values of ϵ' and ϵ'' by assuming that, in the δ region the relaxation is solely due to dipolar reorientation of water. We assumed that the tissues are suspension of low permittivity non conducting spheres in water and used Maxwell's relation to calculate the volume fraction of the solid in the tissue[20] where p is the volume function of the tissues.

$$\frac{\epsilon_{mixture}}{\epsilon_{water}} = \frac{1-p}{1+\frac{p}{2}} \dots\dots\dots(6)$$

The dielectric value at 2.5GHz was used for the calculation since 2.5GHz is much greater than the relaxation frequencies in the dispersion region. The results show a good agreement with some of the available data.

We calculated the volume fraction of the protein present by using the ϵ' and ϵ'' values and Raleigh relationship [19].

$$\epsilon_{\alpha} = \epsilon_{\omega} \left[\frac{\epsilon_p(1+\Phi) + \epsilon_{\omega}(1-\Phi)}{\epsilon_{\omega}(1+\Phi) + \epsilon_p(1-\Phi)} \right] \dots\dots\dots(7)$$

where ϵ_{α} refers to a frequency far above the relaxation frequency, Φ is the volume fraction of the protein, ϵ_p is the dielectric value of protein assumed as 4.0 at 2.5GHz.

Table III: Concentration of Protein per Deciliter of Different Biological Tissues.

Sample	Density of tissue gm/cc	Protein fraction	Concentration of protein gm/dl of soln
Liver	1.01	0.24	23.76
Heart	1.13	0.211	18.76
Muscle	1.17	0.272	23.24
Kidney	1.06	0.269	25.38
Brain	1.05	0.23	21.90

The reflection coefficient of corn syrup samples were measured using the coaxial probe and the network analyzer set up. The dielectric constant is calculated which is depicted in Figure.4.

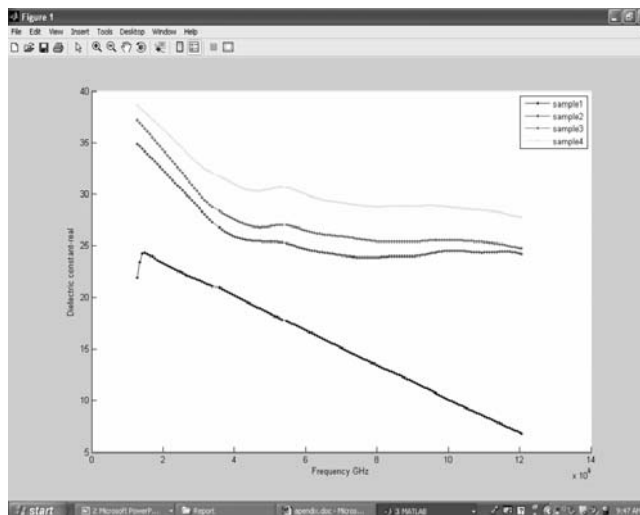


Figure 4: Permittivity of corn syrup samples a function of frequency.

It can be seen that corn syrup in various concentrations have their dielectric constant similar to that of tissues. Hence by varying the saline and corn flour composition we can make tissue equivalent samples. The dielectric constant of corn syrup of few samples were compared with the data available in [21] and found to be in agreement in the frequency range from 1GHz to 3GHz.

Conclusion

The present study proves that the coaxial cable method can be used for the accurate measurement of dielectric property information for a wide range with a single sensor. The experimental values of dielectric property information of various tissues, its relaxation effects, spread of relaxation, volume fraction of solid content in tissues, concentration of protein in tissues suggests the potential of microwaves in the field of diagnostic and therapeutic medical applications. The work also suggests that corn syrup in different concentrations can be used as a tissue equivalent. The research work conducted in this paper is expected for microwave imaging applications.

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