A Simple Experimental Set-up for the Determination of the Complex Dielectric Permittivity of Biological Tissues at Microwave Frequencies

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Abstract – **In this paper a simple experimental set-up is presented to determine the complex dielectric permittivity of biological tissues at the industrial frequency of 2.45 GHz. For this purpose, the scattering parameters of biological samples, which are placed in a sample holder inside a waveguide, are measured and compared with those obtained from numerical analysis of the sample using a FE technique with an adaptive mesh. Systematic errors are minimized by a precise calibration of the experimental system. The results obtained are in very good agreement with well-known published data. The simplicity of the experimental set-up makes this technique a very practical tool for detecting and quantifying changes in the complex dielectric permittivity of organs poisoned with heavy metal pollutants.**

I. Introduction

A living body is made up of a complex structure of biological tissues with very dissimilar electric properties (dielectric permittivity ε and conductivity σ). These properties are, to a great extent, responsible for the interaction of electromagnetic fields with molecules and biological supermolecular structures. Information about the dielectric properties of biological systems is essential to RF dosymetry. Measurements of tissue dielectric properties is important because it provides information necessary for calculating RF power absorption by biological models and for constructing tissue-equivalent models. Also, many biophysical interaction mechanisms of EM fields with biological systems can be inferred from the characteristic behaviour of tissue permittivity as a function of frequency.

At frequencies below 100 MHz, methods based on the impedance bridges are satisfactory for measuring the electrical properties of tissue samples. However, above 300 MHz complex permittivity measurements are not straightforward and the results are subject to greater error. In this frequency range, a distributed-circuit approach rather than a lumped-circuit approach is required because the sample size is usually a considerable fraction of a wavelength. In distributed-circuit techniques, the sample is typically placed in or at the end of a section of transmission line or waveguide. The complex reflection and transmission coefficients are measured instead of the sample impedance.

In this paper a simple experimental set-up is presented to determine the complex dielectric permittivity of biological tissues at the industrial frequency of 2.45 GHz. The scattering parameters of a biological sample, which is placed in a sample holder inside a waveguide, are experimentally determined. These are then compared with those obtained from numerical analysis of the system sample-waveguide by using a finite element (FE) technique with an adaptive mesh. Random errors are taking into consideration and a precise calibration of the experimental system ensures that systematic errors are minimized.

II. Biological Tissues And System Set-up

For this work, different samples of a thickness up to 2 mm of liver, lung, kidney, muscle and pancreas from male Wistar rats were available. In order to ensure no loss of moisture content, the samples were kept in Petri plates containing humidified cotton (NaCl 0.8%), closed hermetically with parafilm and kept at 0° C until the microwave measurements of the dielectric permittivity were made, usually less than thirty minutes after the sample tissue had been available.

The experimental determination of the dielectric complex permittivity was performed by measuring the reflection (S_{11}) and transmission (S_{21}) complex coefficients of a sample of biological tissue by using a vector network analyzer (VNA). The measurements were made at the industrial frequency of 2.45 GHz. For this purpose, a sample holder formed by a methacrylate block with a rectangular cavity, 44 mm long, 11 mm high and 2 mm thick was designed. The complex permittivity of the block was measured experimentally at 2.45 GHz and found to be $\varepsilon_r = 2.6$ and $\sigma = 4.96.10^{-4}$ S/m. The contribution of the dielectric loss of the methacrylate with no sample is taken into account in the calibration of the measuring system. The block is divided into two pieces to facilitate the positioning of the sample as shown in Figure 1. The methacrylate block completely fills a section of WR430 waveguide suitable for work within the range 1.7 to 2.6 GHz. At the selected operating frequency, the length of the sample (11 mm) is very small compared to the wavelength in the guide (148 mm) and therefore it may be assumed that a uniform power is applied to the whole sample placed at the center of the waveguide. A

coax-to-waveguide transition was placed at each end of the WR430 waveguide section and semi-rigid coaxial cables were used to connect each transition to the VNA. Microwave measurements were made at controlled room temperature (27°) and thermal effects during the measurements were negligible as the RF power applied to the sample was very low (-3 dBm)

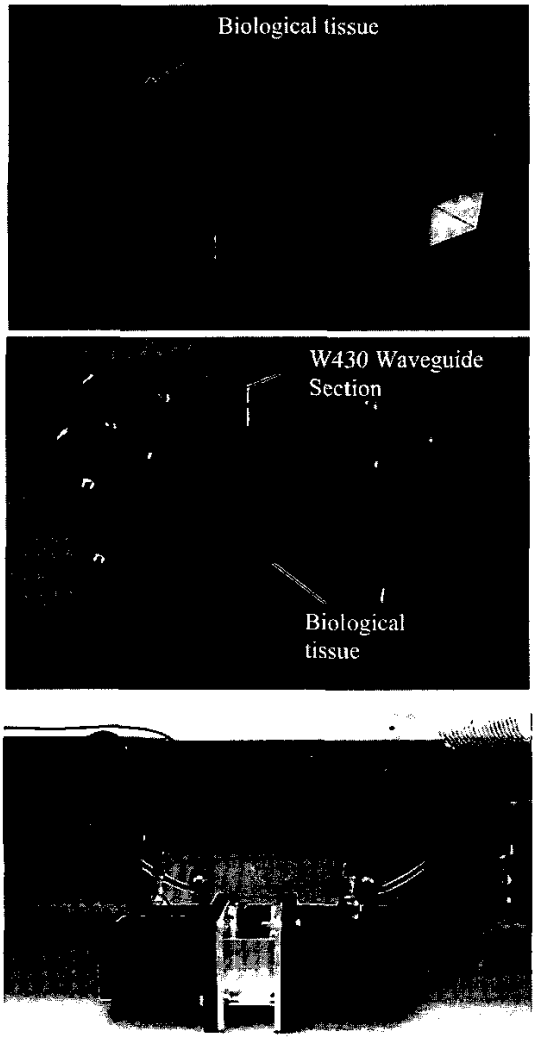

Fig.1. Sampler holder and experimental set-up for the measurement of the complex permittivity.

III. Random Errors

The main sources of random error are the accuracy of the value of the tissue sample volume (968 mm^3), the variation of the content of water or moisture and the intrinsic biological differences that exist among tissue samples. The first one is minimized by the design of the methacrylate sample holder that tightly encloses the sample. The use of translucent methacrylate makes it possible to thoroughly observe the sample inside the block, and, the effects of moisture absorption in this plastic are negligible during the very short time spent in the measurements. With respect to the second source of error, microwave measurements were repeated after 24 hours, following the same procedure for storing and handling tissues. The results obtained showed no significant differences compared to the results from freshly available samples and therefore, any variation observed in the complex permittivity of the samples due to the loss of water or moisture may be disregarded. This fact was confirmed by the repetitive results obtained from measurements showing deviations less than 3.5% and 17% for ε and σ respectively. For the intrinsic biological differences of the tissues, it must be pointed out that by simple ocular inspection some lung samples appeared to be inflated and thus showed lower corresponding permittivity ($\varepsilon_r = 20$) and conductivity values ($\sigma = 2$ S/m) compared to those corresponding to the deflated samples. The values used in this analysis are for deflated samples.

The calibration of the measuring system was performed by using the WR430 waveguide section and three precision waveguide standard loads (short, open and broadband) and the error correction routines integrated in the internal processor of the VNA. Once the experimental system was calibrated at the measuring frequency of 2.45 GHz, the absolute error for the magnitude and phase of the scattering parameters S_{ij} were 0.005 and 0.1 degree respectively, which, in the worst case, correspond to errors of 1.5% for the permittivity and 7% for the conductivity.

IV. Numerical Methods

In this paper a numerical analysis [1]-[2], based on the finite element (FE) technique, of the electromagnetic-field distribution inside the WR430 waveguide section containing the sample of biological tissue was performed. The full Maxwell equations are solved considering a discretization of the geometry into tetrahedral elements. The electric field value at points inside each tetrahedron is interpolated from the values at the vertices of the tetrahedron. The resulting matrix equation for the field values at the mesh nodes is solved by an iterative method and a solution is found. Due to the fact that the dimensions of the biological sample are significantly smaller than the dimensions of the WR430 waveguide section, an adaptive mesh is used so that the size of the basic tetrahedron is varied for the different regions. The accuracy of this technique is conditioned by the smallest size of the mesh single element. In the present analysis 24000 and 12000 basic tetrahedra were used for the tissue and the sample holder respectively.

In order to keep the computational resource requirements reasonable, the computational domain is truncated to a radiation region formed by the waveguide which has perfect conductor walls and the input and output reference planes. The position of these two planes corresponds exactly with the experimental set-up reference planes.

Initially, an approximate value for the tissue complex permittivity is assumed, and for this initial value the

scattering parameters S_{11} and S_{21} are obtained from the field analysis. For each analyzed biological tissue, four parameters, two moduli and two phases are analytically obtained. These four values are compared with the experimental ones at the same reference planes. An iterative process with different values for the complex permittivity is applied until a full match is obtained between the four experimental and analytical values.

V. Results And Discussion

Table I shows the values and the standard deviation for the permittivity ε and the conductivity σ for the different tissues. These values are in good agreement with well-known published data [3]-[5].

Tissue	Complex permittivity	
	ε_r	σ (S.m^{-1})
Liver	42.6 ± 0.96	1.52 ± 0.08
Lung	47.36 ± 0.69	1.64 ± 0.09
Kidney	49.84 ± 1.09	1.77 ± 0.21
Pancreas	41.7 ± 0.78	1.58 ± 0.09
Muscle	49.5 ± 0.64	1.77 ± 0.05

TABLE I
Measured dielectric properties of tissues

As tissues and cells are exposed to metal pollutants, toxic chemicals and hazardous waste, they may be poisoned to a point where their electric properties may be severely altered. To test these changes, the measurements were repeated for the same kind of tissues from Wistar rats previously treated with two pollutant metals such as lead and cadmium with intraperitoneal doses of 0.05 and 0.02 mg/gbw respectively. The results of Table II show significant differences in the permittivity with respect to the values of Table I for the untreated tissues. These variations can be correlated with the variations of various biochemical and hematological parameters.

Tissue	Complex permittivity	
	ε_r	σ (S.m^{-1})
	Lead	
	Cadmium	
Liver	45.4 ± 1.38	1.20 ± 0.16
	42.50 ± 0.8	1.35 ± 0.18
Lung	38.99 ± 1.34	1.19 ± 0.10
	40.75 ± 1.33	1.19 ± 0.09
Kidney	45.70 ± 1.18	1.21 ± 0.20
	44.17 ± 0.98	1.08 ± 0.10
Pancreas	46.83 ± 1.23	1.40 ± 0.14
	51.99 ± 1.04	1.20 ± 0.13
Muscle	48.14 ± 0.69	1.19 ± 0.22
	45.67 ± 1.37	1.10 ± 0.09

TABLE II
Dielectric properties of tissues treated with Pb and Cd

VI. Conclusions

The results obtained show that the simple experimental set-up combined with the FE numerical technique can be very useful for measuring the complex dielectric permittivity of biological tissues. It has also been shown that changes in the electrical properties of biological samples are easily detected and quantified.

The findings here presented may be of interest for the toxicological determination of the damage of tissues due to heavy metal pollutants, e.g. the assessment of minimum doses. Finally, the study presented in this paper may be a good starting point for a more extensive research on the physiological mechanisms that are responsible for tissue alterations.

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References

[1] Muñoz S., Sebastian J.L., Sancho M. and Miranda J.M. *A study of the electric field distribution on rod shape cells from direct RF exposure.* Phys. Med. Biol.48, (2003), 1649-1659.

[2] Sebastián J. L, Muñoz S., Sancho M. and Miranda J. M. *Modelling the internal field distribution in human erythrocytes exposed to RF radiation.* (2004) Bioelectrochemistry 64, 39-45.

[3] Gabriel C., Gabriel S. and Corthout E. *The dielectric properties of biological tissues: I. Literature Survey.* (1996), Phys. Med. Biol. 41: 2231-2249.

[4] Gabriel S., Lau R. W. and Gabriel C., *The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz.* (1996), Phys. Med. Biol. 41: 2251-2269.

[5] Gabriel S., Lau R. W., Gabriel C., *The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues.* (1996), Phys. Med. Biol. 41: 2271-2293.