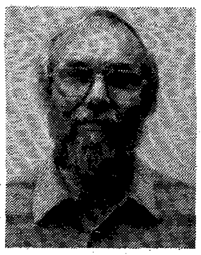

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Dielectric Loss in Biogenic Steroids at Microwave Frequencies

R. ARUNA AND J. BEHARI

Abstract—**Dielectric loss in steroids has been measured in solid form at 9.4 GHz and in nonaqueous solutions at 3.3 and 9.4 GHz. The method for solutions consists of measurement on standing-wave pattern in front of a column of liquid of varying length and concentration, contained in a short-circuited dielectric cell. Keeping the concentration within the limits of dilute solutions, dipole moment and relaxation time of Cholesterol, Progesterone, and Testosterone have been evaluated. Mechanisms responsible for dielectric loss and its trend of variation in the three steroids are presented. The solid phase measurements were carried out by cavity perturbation technique on powders and crystal values for ϵ' and ϵ'' were evaluated. The difference in ϵ'' values of the three steroids in the two phases is attributed to the difference in the mechanism of microwave absorption. However, identical values of ϵ' are obtained.**

I. INTRODUCTION

THE EFFECT OF microwaves on biological systems has assumed an interesting dimension in recent years [1], [2]. This is largely due to increasing use of microwaves in medical diagnosis and therapy. The energies of microwave quanta rule out the possibility of direct effects, such as intermolecular bond breaking or intramolecular alterations at the molecular level, that are produced by ultraviolet and other ionizing radiations.

The propagation characteristics of electromagnetic waves through a biological medium depends upon its electrical properties. The significant electrical property of a system which determines the impedance offered to the incident wave is the electric permittivity of the medium [3]. Since all biological media are lossy, attenuation occurs as energy is absorbed. Attenuation and accompanied phase shift are dependent on the dielectric properties of the medium characterized by complex permittivity ϵ^* of the medium denoted as $\epsilon' - j\epsilon''$. The possible biological effects of microwave exposure can be evaluated quantitatively by considering the probable molecular interactions with biomolecular liquids. This requires, besides loss tangent, an evaluation of relaxation time and dipole moment. Dipole moment is a direct measure of charge asymmetry, while relaxation time provides information regarding the immediate environment of the molecule. To isolate the effect of the solvent, we have determined the complex permittivity in crystalline form as well.

Most of the work pertaining to biological effects of microwaves are measurements on tissues or on composite

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TABLE I

Chemical	Source
Cholesterol	Sigma
Progesterone	C.S.I.R. Centre for Biochemicals, India.
Testosterone	C.S.I.R. Centre for Biochemicals, India.
Benzene	BDH, Analar.
Carbon tetra chloride	BDH, Analar.

systems. In contrast to a large volume of data available on water-soluble biomolecules [4], [5], those on water insoluble ones are rather few. A number of steroids though present in traces in a living system play a vital role in the development and maintenance of the organism. These are the steroid hormones of the adrenal and gonads. The precursor for all these steroid hormones is Cholesterol synthesized by the adrenal glands. Of many steroids present in living organisms, Cholesterol, Progesterone, and Testosterone are soluble in simple nonpolar solvents like benzene and carbon tetrachloride. Measurements on dilute solutions in nonpolar, nonviscous solvents seem to be interpreted most easily, since no particular effects due to the surroundings of the polar molecules are expected for these systems.

II. Materials and Method

The source of the chemicals used in the study is indicated in Table I. The measurements were carried out throughout at room temperature.

A. Measurement on Solutions

The permittivity and loss tangent were determined by measurement on standing waves in front of a column of dielectric enclosed in a waveguide cell. Microwaves traveling in the TE_{10} mode, reflected by a perfectly reflecting surface, superpose with the incident wave setting up standing waves. The separation of the first minimum from the front face of the sample, x_0, is a measure of the dielectric constant where as the reduction in the voltage standing-wave ratio (VSWR), ρ, measures the attenuation caused by the sample. The length of the liquid column is varied by moving the adjustable short at the end of the waveguide cell.

The experimental setup is shown in Fig. 1. Measurements are carried out at two frequencies, one in the S band (3.3 GHz) and other in the X band (9.4 GHz), under identical conditions. Permittivity and loss tangent were computed using the relations given below.

B. Measurement on Powders

The permittivity and loss factor in the powder form were measured by cavity perturbation technique [6]. The sample filled in a thin walled capillary tube was inserted through a small hole at the center of the wider wall of a rectangular cavity resonating at 9.4 GHz in the TE_{103} mode. The shift in the resonant frequency, f, and the change in quality factor, Q, are related to the real and imaginary parts of complex permittivity as discussed below.

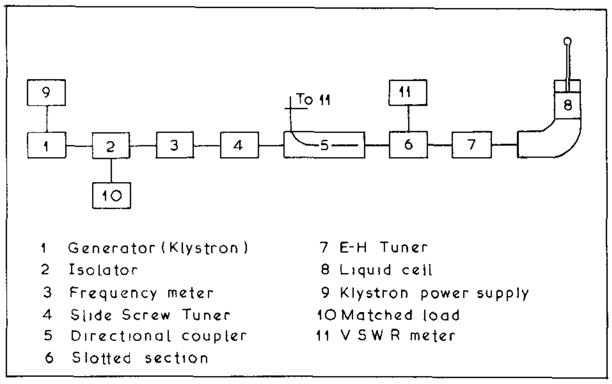

Fig. 1. Schematic diagram of setup for measurement on liquids.

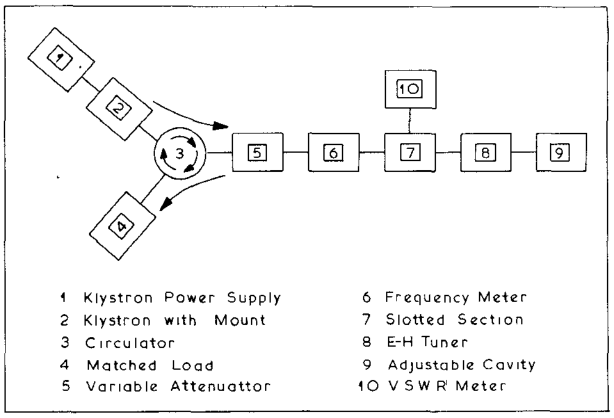

Fig. 2. Schematic diagram of setup for cavity perturbation technique.

The experimental setup is shown in Fig. 2. The powder was packed in the capillary tube by gentle tapping and the density was measured. Care was taken to ensure uniform packing in all specimens in each case.

III. Theoretical Background and Analysis of Data

A. Measurement on Solutions

Because the solutions involve very low losses, the following method of calculation may be used [7]. The phase shift β_d produced by a sample of length d is calculated from

$$\frac{-\lambda_g \tan\dfrac{2\pi x_0}{\lambda_g}}{2\pi d} = \frac{\tan\beta_d}{\beta_d} \tag{1}$$

where λ_g is the guide wavelength. Then ϵ' and loss tangent are computed from

$$\epsilon' = \frac{1/\lambda_c^2 + (\beta_d/2\pi d)^2}{1/\lambda_c^2 + 1/\lambda_g^2} \tag{2}$$

and

$$\tan\delta' = \frac{\dfrac{\lambda_g}{\pi d \rho}\left[1-(\lambda_0/\lambda_c)^2 \cdot 1/\epsilon'\right]\left(1+\tan^2\dfrac{2\pi x_0}{\lambda_g}\right)}{(1+\tan^2\beta_d)-\tan\beta_d/\beta_d} \tag{3}$$

where λ_0 is the free-space wavelength and λ_c is the cutoff wavelength. The wall losses are usually eliminated using the dissipation factor of the empty waveguide [7]. Apart from wall losses, the pure solvent also exhibits a finite loss. Hence the loss tangent due to the solute alone is given as

$$\tan\delta = \tan\delta'_{\text{soln}} - \tan\delta'_{\text{solv}}.$$

The values of relaxation time and dipole moment were arrived at on the basis of Debye's theory [8] of dilute solution of polar solutes in nonpolar sovlents. Measurements were performed at different concentrations, the maximum weight fraction being 0.01.

Debye's equation for molar loss tangent can be rearranged to give

$$\frac{\omega}{\tan\delta} = S\left(\frac{1}{\tau} + \omega^2\tau\right) \tag{4}$$

where

$$S = \frac{6750kT\epsilon_0}{(\epsilon_0+2)^2 N_A \pi \mu^2 C}. \tag{5}$$

Here, ω is the angular frequency, μ is the apparent dipole moment, and τ is the relaxation time of the solute, ϵ_0 is the real permittivity of the pure solvent, C is the concentration of the solute in moles/liter. Denoting the two points of measurement by subscripts 1 and 2,

$$S\tau = \frac{(\omega_1/\tan\delta_1 - \omega_2/\tan\delta_2)}{\omega_1^2 - \omega_2^2} \tag{6}$$

$$S/\tau = \frac{\omega_1\omega_2(\omega_1/\tan\delta_2 - \omega_2/\tan\delta_1)}{\omega_1^2 - \omega_2^2}. \tag{7}$$

Relaxation time, τ, and apparent dipole moment μ in solution follow from (5)–(7).

A number of mixture relations [9] have been derived for the permittivity of a mixture in terms of the permittivities of the components. Usually they are generalized for complex permittivities. Since loss tangent of dilute solutions in nonpolar solvents is very small, the Landau–Lifshitz formula yields, for permittivity of the solute,

$$\epsilon_{\text{solute}}'^{1/3} = \frac{1}{y_1}\left\{\epsilon_{\text{soln}}'^{1/3} - y_2\epsilon_{\text{solv}}'^{1/3}\right\} \tag{8}$$

where y_1 and y_2 are the volume fraction of the solute and solvent, respectively.

B. Measurement on Powders

If f_p and Q_p are the resonant frequency and Q of the cavity perturbed by the sample filled tube, and f_t and Q_t that of the cavity perturbed by the tube alone, perturbation theory [10] yields

$$\epsilon'_p = 1 + 0.5\frac{V_s}{V_c}\left\{\frac{f_t - f_p}{f_p}\right\} \tag{9}$$

$$\epsilon''_p = 0.25\frac{V_s}{V_c}\left\{\frac{1}{Q_p} - \frac{1}{Q_t}\right\} \tag{10}$$

where V_c and V_s are the volumes of the cavity and sample, respectively. The experimental values of permittivity and loss factor in each case pertain to the packing fraction. Attempts have been made to correlate the powder and bulk values of complex permittivities [11], [12]. We have chosen the generalized Bottcher's formula [11] since it involves no approximation regarding the magnitude of the loss tangent.

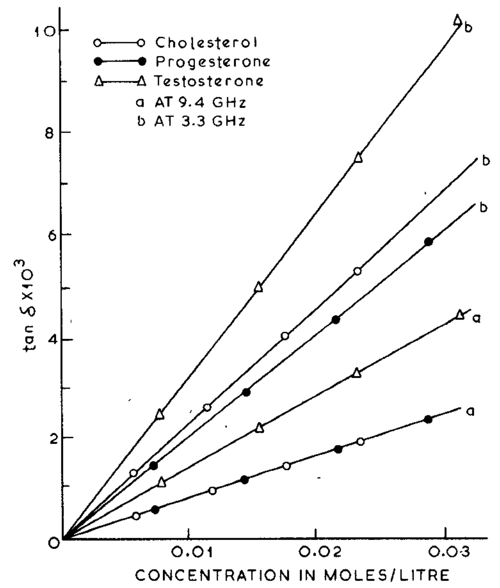

Fig. 3. Variation of loss tangent with concentration in benzene.

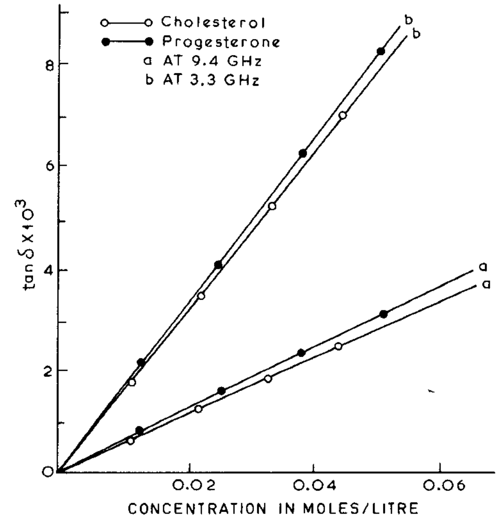

Fig. 4. Variation of loss tangent with concentration in carbon tetrachloride.

IV. Results and Discussion

The $\tan\delta$ versus concentration curve for different solutions obtained at 9.4 and 3.3 GHz are shown in Figs. 3 and 4. The estimated error in $\tan\delta$ values were ± 1 percent. The values of τ and μ computed from the data presented are tabulated in Table II.

The observed relaxation time of Progesterone and Testosterone agree fairly well with values calculated using Debye's theory of microscopic relaxation time. This is to be expected since the molecules are comparatively large with respect to the solvent molecules and their axial ratio <2 [13]. The difference between the observed values and the calculated values for Cholesterol may be due to larger axial ratio in this case. τ_{obs} lies between the relaxation times

TABLE II
RELAXATION TIME[(a)] AND APPARENT DIPOLE MOMENT OF THE SOLUTES

Solute	Solvent	$\tau_{obs} \times 10^{12}$ sec	μ in D	$\tau_D \times 10^{12}$ sec.
Cholesterol	Benzene	252.3	4.79	152.4
Progesterone	Benzene	108.7	3.23	93.0
Testosterone	Benzene	85.7	3.74	77.8
Cholesterol	CCl_4	376.1	4.87	227.8
Progesterone	CCl_4	162.1	3.28	139.0

(a) at 30°C.

TABLE III
MOLECULAR DIMENSIONS [14] AND DENSITY [15] OF THE STEROID

Name	Mol. wt.	Molecular Dimensions	Density
Cholesterol	386.7	20A° x 7.2 A° x 5.0A°	1.067
Progesterone	314.4	12.3A° x 6.9A° x 5.14A°	1.166
Testosterone	288.4	11.01A° x 6.03A° x 5.58A°	1.27*

*estimated value.

of the long and short axes calculated using Perrin's equation [5]: 325.2×10^{-12} s and 164.6×10^{-12} s in benzene and 486.1×10^{-12} s and 246.0×10^{-12} s in CCl_4. However, the ratio of observed relaxation times in CCl_4 and benzene is in the ratio of the viscosity of the two solvents as predicted by Debye's theory.

In this context, it may be mentioned that in many cases, dielectric absorption of the intramolecular processes is not readily separated from the overall rotation of the molecules and hence interpretation of the dielectric data solely in terms of overall relaxation of the molecules may not be valid. Each of the solutes in the present study possesses a rotating group. The dielectric absorption in most aromatic compounds, having a rotatable polar group, is characterized by two discrete relaxation processes—an intramolecular, having a small relaxation time; and a molecular, with a relatively large relaxation time [16]. The characteristic time for group reorientations falls in the far-infrared region. Hence, it can be assumed that this process would not contribute to loss at frequencies less than a few gigahertz.

Table IV represents the powder data for the solutes and the corresponding crystal values. The permittivity of the solute obtained from solution data is given in the last column of the table. This value agrees fairly well with the crystal value obtained from powder data. This may be due to the absence of specific solute solvent interactions for the molecules dispersed in a nonpolar solvent. It may be noted that ϵ' increases with increasing dipole moment (Progesterone→Testosterone→Cholesterol). In all the cases under study, the loss factor in solid form shows wide divergence from the loss in solution. This may be attributed to different mechanisms of absorption in the two phases. Dipole relaxation accounts for the loss in solution form, while constrained motional states would contribute to the loss in solid phase. The dilute solutions can be considered to be noninteracting systems in which the maximum loss is determined by the dipole moment of the polar molecule and its concentration, whereas the loss at a particular frequency would also depend on the molecular environment. In contrast, a loss in the solid phase would exhibit very little dispersion at frequencies between a few megahertz to a few gigahertz. Both in the solid form and in solution, these steroids exhibit high loss. Loss in Testosterone is distinctly higher than the loss in Cholesterol and Progesterone.

TABLE IV
PERMITTIVITY AND LOSS FACTOR OF THE SOLUTES IN SOLID STATE AT 9.4 GHz

Solute	ϵ'_p	ϵ''_p	Packing fraction	ϵ'_s	ϵ''_s	$\tan\delta$	ϵ'_{Solute}
Cholesterol	1.828 ±.009	.129 ±.004	.398	3.83	.549	.143	3.86
Progesterone	1.589 ±.008	.144 ±.004	.424	2.70	.492	.182	2.72
Testosterone	1.709 ±.011	.227 ±.006	.411	3.20	.864	.270	3.18

V. CONCLUSION

The two phases considered in the present work exhibit nearly the two extremes of the various types of dielectric response in condensed matter [17]. It is apparent that the behavior of those molecules under physiological conditions would be determined by various factors including the state of the molecule and its immediate environment. Steroids bind to albumin in blood nonspecifically but there are also specific binding proteins for certain steroids. A certain fraction of these molecules is also found in the native state. The binding of steroids to plasma proteins plays an important physiological role, since it is only the unbound fraction which is freely exchangeable with the extravascular and intracellular compartments and has biological activity. The steroid protein complex would relax at a lower frequency than the native molecule. However, the relaxation frequency of the native molecules will not be very much different from the value in nonpolar environments, but the loss would be modified by intermolecular interactions. Local energy changes and possible changes in intermolecular interactions due to absorption of energy from the incident field may have functional implications [18] in a biological system. In view of the foregoing comments, the results presented here would probably provide some basic information regarding the behavior of these molecules in a microwave field.

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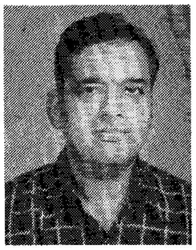

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Analysis of Miniature Electric Field Probes with Resistive Transmission Lines

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***Abstract*—The miniature dipole probe is a useful tool for measuring the electric field at high radio and microwave frequencies. A common design for the probe consists of an electrically short dipole antenna with a diode across its terminals; a resistive, parallel-wire transmission line transmits the detected signal from the diode to the monitoring instrumentation. The high resistance per unit length of the transmission line reduces the direct reception of the incident field by the line and also reduces the scattering of the incident field by the line. In addition, the resistive transmission line serves as a low-pass filter in the detection process. In this paper, the effect of the resistive transmission line on the operation of the miniature field probe is analyzed. Specifically, the reception of the incident signal by the transmission line is compared with that of the dipole. The scattering of the incident signal by the transmission line is studied by means of the scattering cross section, and the limitation imposed on the measurement of amplitude-modulated signals by the low-pass filtering by the resistive line is examined. The results of the theoretical analyses are presented as simple formulas which are useful in the design and optimization of the probe. The theoretical results are shown to be in good agreement with measurements.**

I. INTRODUCTION

IN MANY practical applications of electromagnetism at high radio and microwave frequencies, an accurate measurement of the electric field in free space or in a material medium is required. Examples are the calibration of electromagnetic shielded rooms and anechoic chambers, the measurement of the near field of transmitting antennas,

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