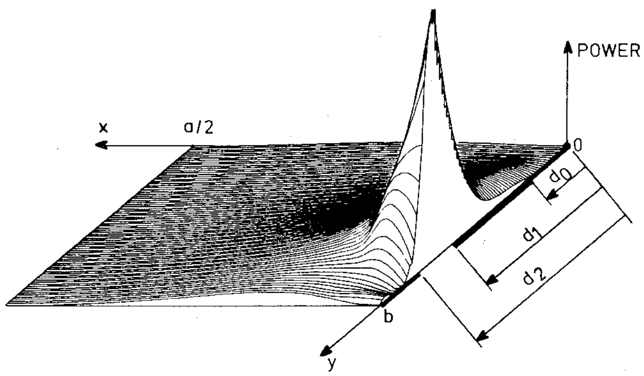
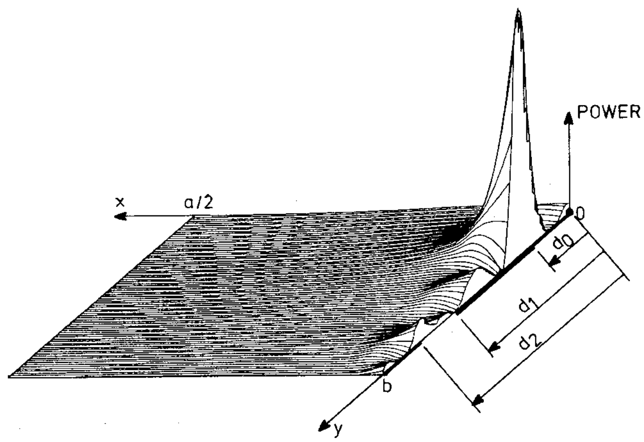


(a)



(b)

Fig. 14. Power density on the half cross section of finline. The power is concentrated on the slot. The InSb thickness is $2\times1\ \mu m$, finline isolator $d_0 = 0.2b$, $d_2 = 0.8b$, $f = 36$ GHz, $B_0 = 0.8T$. This is the forward case. (b) Power density on the half cross section of finline. The power is concentrated on the semiconductor. The parameters are given in Fig. 14(a). This is the backward case.

[6] S. A. Schelkunoff, "Generalized telegraphist's equations for waveguides," *Bell Syst. Tech. J.*, vol. J.31, pp. 784–801, July 1982.
[7] R. M. Arnold and F. J. Rosenbaum, "Nonreciprocal wave propagation in semiconductor loaded waveguides in the presence of a transverse magnetic field," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 57–65, Jan. 1971.
[8] J. L. Amalric, "Contribution à l'étude de l'effet de déplacement de champ dans les guides chargés par les lames semiconductrices," thèse de doctorat d'etat INP Toulouse, France, 1978.
[9] H. Hofmann, "Dispersion of planar waveguides for millimeter wave application," *Arch. Elek. Übertragung*, vol. 31, pp. 40–44, Jan. 1977.
[10] E. Pic, S. Tedjini, and C. Nasrallah, "Une nouvelle ligne integrable millimétrique: la finline," *Annales des Télécommunications*, vol. 37, no. 11–12, pp. 461–476, 1982.
[11] S. Tedjini, "Contribution à l'étude d'un isolateur à semiconducteur pour ondes millimétriques: application à la fin-line," doctorat thesis, INP Grenoble, France, 1982.
[12] B. R. MacLeod and W. G. Way. "A 35-GHz isolator using a coaxial solid state in a longitudinal magnetic field," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 510–516, June 1971.
[13] M. Kanda and W. G. May, "Hollow-cylinder waveguide isolators for use at millimeter wavelengths," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 913–917, Nov. 1974.

Biological Tissues Characterization at Microwave Frequencies

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***Abstract*—The present work is concerned with the measurement of dielectric permittivity and conductivity of various high loss tissues from freshly sacrificed animals. The measurement makes use of the 'infinite sample' technique which involves mounting of the sample in a rectangular waveguide system excited in the TE_{10} mode at 9.4 GHz. A more complex system consisting of skin-fat-muscle combination is also studied. An evaluation of relaxation times is made in all the cases. It is hoped that these data will be relevant in further quantifying the available results in this frequency range.**

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I. Introduction

Biological effects of microwave radiation have been the focus of various research efforts in the last decade. Key to this is the determination of the complex permittivity (ϵ' and ϵ'') of biological tissues. Although *in vivo* methods have been attempted in the recent past [1], no data are available on dielectric measurements of tissues like stomach, intestine, and heart in the gigahertz frequency range, though some measurements for kidney and liver have been recently reported [2]. In an effort to bridge this gap, a detailed survey has been undertaken of almost all the available biological tissues. The chosen method would have to be one which could be uniformly adopted for all such tissues and at the same time be fairly quick and simple. This would allow measurements on fresh tissues, thus ensuring essential sample configuration. Dictated by these factors, the 'infinite sample' technique was adopted for the measurement of dielectric parameters of high-loss tissues at microwave frequencies.

In order to compare our measurements with those of other techniques [2], we have included some of the tissues like muscle, spleen, and liver, and also the muscle phantom tissue for which fairly reliable data are available [3]. Besides these, tissues like intestine, stomach, spleen, heart, and a more complex system consisting of a skin, fat, and muscle combination were also studied. The measurements were performed at 9.4 GHz. The frequency was chosen to be in the gigahertz range in view of the possibility of the use of high-frequency electrical energy as an effective method of selectively heating local masses of tissues, while the surface heating of tumors has also been proposed [4].

II. Theoretical Background of the 'Infinite Sample' Technique [5]

When a physically reasonable length of the sample dissipates a sufficiently large portion of the microwave energy entering the sample so that no energy is reflected to the input terminal, the sample may be considered to be of 'infinite length'. Thus, making use of the 'infinite sample' technique, the measurement requires the determination of essentially only the normalized input impedance at the sample face. The dielectric permittivity and the loss

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tangent can be computed using (1) below. For guides with propagating H(TE) modes (such as TE_{10}, the dominant mode in rectangular waveguide), the expression for ϵ^* is

$$\epsilon^* = \left[1+\left(\frac{\lambda_c}{\lambda_g}\right)^2\right]^{-1} + \left[1+\left(\frac{\lambda_g}{\lambda_c}\right)^2\right]^{-1}\left[\frac{\gamma - j\tan[K(D-D_R)]}{1-j\gamma\tan[K(D-D_R)]}\right]^2 \quad (1)$$

where

$$k = 2\pi/\lambda g,$$

λ_c cutoff wavelength in the waveguide,
λ_g guide wavelength,
γ voltage standing-wave ratio,
D_R position of minimum in shorted waveguide without sample,
D position of minimum with sample.

III. Methods and Materials

Measurements were performed at 9.4 GHz on tissues from freshly sacrificed rats. The animals were sacrificed by an overdose of anaesthesia (sodium nembutal solution). Each time a fresh animal was sacrificed, the measurements were taken immediately after. Twenty observations were taken for each tissue.

Measurement of Dielectric Parameters

The method involves mounting of the sample in a rectangular waveguide excited in the TE_{10} mode. The basic equipment for this measurement is shown in Fig. 1. The slotted line was terminated with a short circuit at a definite plane and the position of the minimum D_R in the slotted line was noted down. The short circuit was replaced with the line containing the sample. The face of the sample nearest the slotted line was made to coincide with the terminal plane exactly at which a short circuit was accurately placed. No change in D and r with increasing sample thickness, indicated that the sample was long enough to be considered infinitely long. The values of r and shift in minima position $(D - D_R)$ were noted down for this case. The dielectric constant, conductivity, and the loss tangent of various tissues and a three-layer system consisting of skin, fat, and muscle combination with skin facing the incident beam, were computed using (1) above.

IV. Results and Discussion

The relative dielectric constant and the loss tangent of various tissues is presented in Table I. The technique was checked by making measurements on muscle phantom material and comparing them with values obtained by others. Our averaged measured parameters for this turns out to be $\epsilon' = 40.1$, loss factor, $\tan\delta = 0.51$, and conductivity $\sigma = 10.6$ mho/m, in fair agreement with reported results [6]. The dielectric parameters for muscle, liver, spleen, and kidney as obtained here are also in good agreement with the reported values [2], [7].

It is evident from the data obtained here that the values of ϵ' for most of the tissues lie in the same range, though the ones for stomach and intestine are slightly higher. This may be attributed to the higher ionic content of these tissues, as minute concentrations of an electrolyte usually impart considerable conductivity, to the liquid medium [8].

The characteristic frequency ($f < f_c$) can be estimated from the relation [9]

$$f_c = \frac{(\epsilon_0 - \epsilon_\infty)2\pi f^2 \epsilon_\gamma}{\sigma - \sigma_0} \quad (2)$$

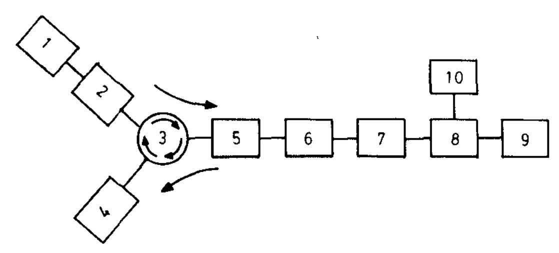

Fig. 1. Schematic diagram of setup for infinite sample technique.

where ϵ_γ is the free-space permittivity, $(\sigma - \sigma_0)$ is the conductivity increase, and $(\epsilon_0 - \epsilon_\infty)$ is the permittivity decrease due to this dispersion, from much below and much above the relaxation frequency, respectively. Table I gives the relaxation frequency for various tissues, which is seen to be close to that of water at room temperature, thus characterizing the rotational mobility of the tissue water. Taking σ_0 and σ to be, respectively, tissue conductivities at 0.1 GHz [7] and 9.4 GHz, and using the known dielectric properties of water [10], we estimate the volume fraction of tissue water, which is found to be in agreement with the water content of different tissues [11].

Assuming that the tissue is electrically equivalent (at frequencies above 1 GHz), to a suspension of low permittivity nonconducting spheres in water, the volume fraction p of nonconducting spheres can be estimated using Maxwell's theory [7], using the relations

$$\frac{\epsilon_{\text{mixture}}}{\epsilon_{\text{water}}} = \left(\frac{1-P}{1-P/2}\right). \quad (3)$$

Figs. 2 and 3 show the variation of ϵ' and σ with solid content of tissue where it can be seen that the values of real dielectric constant and the conductivity decrease with the increase of total solid content of the tissue.

V. Conclusion

It is apparent that the behavior of the molecules under physiological conditions would be determined by various factors, including the state of the molecule and its immediate environment [12]. From what was said about the data on dielectric parameters and relaxation frequencies of water and various tissues, it is evident that the dielectric behavior of tissues at microwave frequencies is mainly influenced by the water content of the tissues. We find that the relaxation frequency of most of the tissues (22–24 GHz) under consideration are close to that of bulk water (25 GHz). The divergence being attributed to the tissue solid content.

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TABLE I
MEASURED RAT-TISSUE CHARACTERISTICS AT 9.4 GHz

Tissue	Permittivity (other workers [2]) *	Loss Tangent	Conductivity mho/m (other workers [2])*	Relaxation Frequency GHz
Stomach	62.10 ± 0.89	0.41	14.5 ± 0.91	22.7
Intestine	61.9 ± 2.69	0.45	14.5 ± 1.31	22.7
Muscle	40.4 ± 0.52 (40 - 42)*	0.53	11.2 ± 0.38 (8.3)*	23.6
Spleen	40.5 ± 0.32 (38 - 40)*	0.50	10.4 ± 0.26	24.8
Kidney	39.7 ± 0.54 (42 - 43)*	0.47	9.88 ± 0.35 (3 - 4)*	23.7
Heart	39.60 ± 1.2	0.47	9.76 ± 0.25	24.6
Liver	34.0 ± 0.53 (34 - 38)*	0.47	8.25 ± 0.13 (5.8 - 7)*	24.1
Skin-Fat-Muscle	13.7 ± 2.27	0.27	2.40 ± 0.10	33.3

Measurements for each type of tissue were made on samples taken from 20 rats. Standard errors are given for permittivity and conductivity measurements.

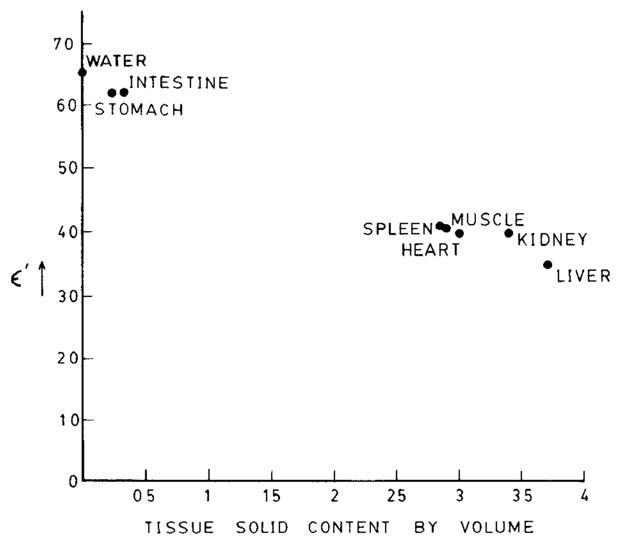

Fig. 2. Variation of real dielectric constant with tissue solid content at 9.4 GHz.

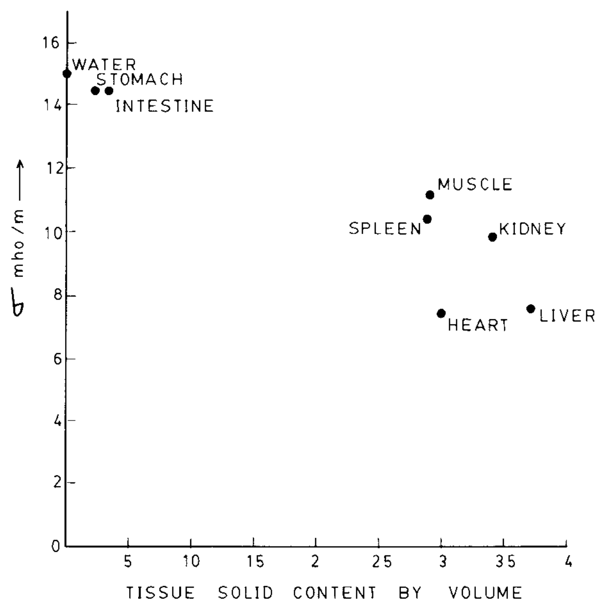

Fig 3. Variation of conductivity with tissue solid content at 9.4 GHz

REFERENCES

[1] E. C. Burdette, F. L. Chain, and J. Seals, "*In vivo* probe measurement technique for determining properties at VHF through microwave frequencies," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, p. 414, 1980.

[2] M. M. Brady, S. A. Symons, and S. S. Stuchly, "Dielectric behavior of selected animals tissues *in vitro* at frequencies from 2 to 4 GHz," *IEEE Trans. Biomed. Eng.*, vol. BME-28, pp. 305–307, Mar. 1981.

[3] S. Baranski and P. Czerski, *Biological Effects of Microwaves*. Pennsylvania: Dowden, Hutchinson and Ross Inc., 1976, p. 60.

[4] B. S. Guru, "An experimental and theoretical study on the interaction of electromagnetic fields with arbitrary shaped biological bodies," a Ph.D. thesis submitted to Michigan State University, 1976.

[5] H. M. Altschular, "Measurement of dielectric constant," in Handbook of microwave measurement. M. Sucher and J. Fox (eds), Polytechnic Press, New York, Vol. II, pp. 495–548, 1963.

[6] A. W. Guy, "Measurement of absorbed electromagnetic power density in biological systems," in *Abstr. Microwave Symp.* (Boulder, CO), 1972, p. 69.

[7] H. P. Schwan and K. R. Foster, "RF field interactions with biological systems: Electrical properties and biophysical mechanism," *Proc. IEEE*, vol. 69, pp. 104–113, Jan 1980.

[8] M. Davies, "Dielectric dispersion and absorption and some related studies in condensed phases," in *Dielectric properties and molecular behaviour*, N. E. Hill and W. E. Vaughan, A H. Price, and M Davies, Eds. London: Van Nostrand, Reinhold, 1969.

[9] H. P. Schwan and K. R. Foster, "Microwave dielectric properties of tissues: Some comments on the rotational mobility of tissue water," *Biophys. J.*, vol. 17, p. 193, 1977.

[10] E. H. Grant, R. J. Sheppard, and G. P. South, *Dielectric Behaviour of Biological Molecules in Solution*. London: Oxford Press, 1978.

[11] P. L. Altman and H. J. Dittmer, Eds., *The Biology Text Book*. Washington, DC: Federation of American Societies for Experimental Biology, 1964, pp. 401–403.

[12] R. Aruna and J. Behari, "Dielectric loss in biogenic steroids at microwave frequencies," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 1209–1213, Nov. 1981.