COMPLEX PERMITTIVITY AND PENETRATION DEPTH OF CERTAIN BIOLOGICAL TISSUE BETWEEN 40 AND 90 GHZ

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Abstract

First measurements of the complex permittivity and penetration depth of millimeter waves in fat and muscle tissue are reported. A new phaseless reduction technique is used. Significant variations of tissue properties after death were found.

Introduction

The dielectric properties and the penetration depth of electromagnetic radiation in various types of biological tissue like muscles, fat and skin has been the subject of intense study for the frequency range extending up to approximately 30 GHz[1,2,3]. Very little is known above this frequency. However, the recent expansion of communications and radar into the millimeter wavelength region as well as the interest in millimeter wave thermography of the human body[4] make it desirable to determine certain electrical characteristics of biological tissue and particularly of the human body.

Methods of Procedure

The high relative dielectric constant ε_r, the relatively high value of conductivity σ, and the softness of biological tissue make it difficult to measure them at the very short millimeter wavelengths. Measurement of the angle of the reflection coefficient as conventionally performed at lower frequencies or with structurally well defined materials like ceramics[5], was found to depend so critically on dimensional variations that an accurate determination was virtually impossible. Therefore only the VSWR obtained from reflection measurements of tissue which was enclosed in a section of standard-height waveguide[6] or placed against the open end of a waveguide[7] could be used. The reflection technique involving the open ended waveguide allowed "in situ" measurements and also made it possible to complete the measurements readily, before an alteration of the tissue characteristics could take place. In a third measurement the insertion loss of a tissue sample enclosed in a waveguide section was determined. Assuming single mode propagation one can determine from this loss the penetration depth δ where the field strength reduces to 1/e of its original value. For operation far above the cutoff frequency of the waveguide this depth δ is related to the complex permittivity of the tissue[7]

$$\bar{\epsilon}=\epsilon'-j\epsilon''=\epsilon_r\,\epsilon_0-j\sigma/\omega=\mu_0/\bar{Z}^2+\pi^2/(\omega^2\mu_0^2 a) \quad (1)$$

by the equation[7]

$$\delta=C_0(\epsilon_r^2\omega^4+\sigma^2\omega^2\epsilon_0^{-2})^{-1/4}\sin^{-1}\left[1/2\arctan(\sigma/(\omega\epsilon_r\epsilon_0))\right] \quad (2)$$

where c_0, ε_0 and μ_0 represent the velocity of light, the permeability and the dielectric constant of free space, respectively. $\bar{Z}$ is the complex impedance of the tissue sample imbedded in a waveguide section of width "a" measured at the radian frequency ω. Another assumption made in the above equation is that multiple reflections within the tissue sample are negligibly small; this assumption is reasonable for high values of ε_r and σ despite of the short sample length ℓ (ℓ = 1.5mm for muscle and ℓ = 6mm for fat).

The method used for the determination of ε_r and σ consisted in calculating ε_r and σ for a given VSWR as a function of the phase angle of the reflection coefficient according to Equ. (1). Given ε_r and σ one can calculate a theoretical value of the penetration depth δ as a function of the phase angle according to Equ. (2). Assuming single mode propagation one can now use the experimentally used value of δ to find the correct phase angle and hence the correct values for ε_r and σ.

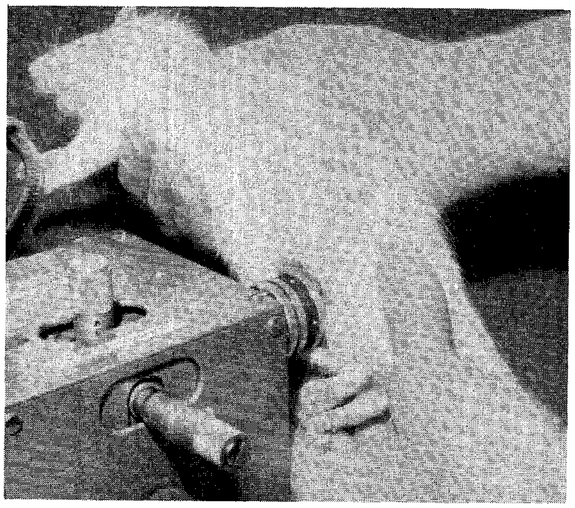

Figure 1. "In situ" measurement of the reflection coefficient of the thigh muscle of an anesthetized albino Sprague-Dawley CD laboratory rat at 47 GHz.

Experiments

The measurements were performed over the frequency ranges 40 to 54 GHz and 85 to 90 GHz. For each of the ranges the basic set-up consisted of a signal source followed by an isolator, precision attenuator, a frequency meter and a slotted line leading to the section of waveguide in which the thin mica window was placed. The mica window helped to control the geometry of the tissue and minimize the generation of higher order propagation modes.[7]

One kind of tissue measured was fat obtained from recently slaughtered cattle; it was returned to the laboratory within 55 minutes of the time that the animal was terminated and within 30 minutes of the time the tissue was removed from the carcass. The tissue was kept in normal saline solution at the body temperature of the animal (100°F). Small pieces of the specimen (about 3/4 inch cubed) were taken for each separate measurement, held up to the end of the guide and then discarded.

Measurements were taken to determine variations in the measured reflection over a period of time. It was found that between two and three hours after the termination of the animal a significant shift in properties did occur. This effect was repeatable, and effectively placed a limit on the amount of time that could be spent for meaningful measurements with a single specimen.

Another tissue measured was muscle tissue from small albino Sprague-Dawley CD laboratory rats. The rats were anesthetized by a peritoneal injection of sodium Nembutal and the muscle tissue of the outer thigh was exposed. The muscle was not excised initially. The rat was held up and the exposed muscle placed against the end of the waveguide as shown in Figure 1. For the transmission measurements muscle tissue was excised from the thigh of the rat, inserted in the waveguide, and pressed against the mica window.

Results and Conclusions

Figure 2 shows the results for the penetration depth δ of fat and muscle. The curve for muscle which exhibits the expected frequency inverse behaviour follows reasonably well the one predicted by Schwan and Li based on data measured at lower frequencies.[3] The curve for fat also agrees within 50% of the extrapolated data of England.[1] The relatively large values of δ for fat of several millimeters around 50 GHz make this range attractive for millimeter wave thermography.[4]

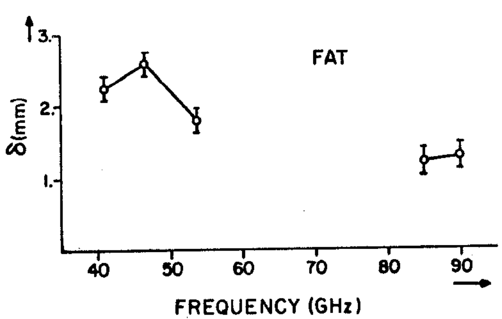

Figure 2a

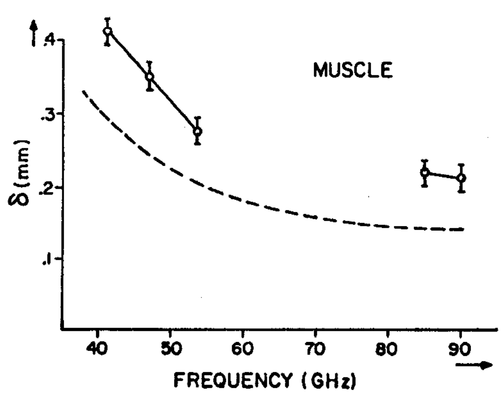

Figure 2b

Figure 2. Measured penetration depth δ versus frequency in fat tissue from cattle (Figure 2a) and muscle tissue from albino Sprague-Dawley CD laboratory rate (Figure 2b) versus frequency. Dashed curve in Figure 2b represents predictions by Schwan and Li.[3]

In Figure 3 the relative dielectric constant and the conductivity for the same tissues are plotted ver-

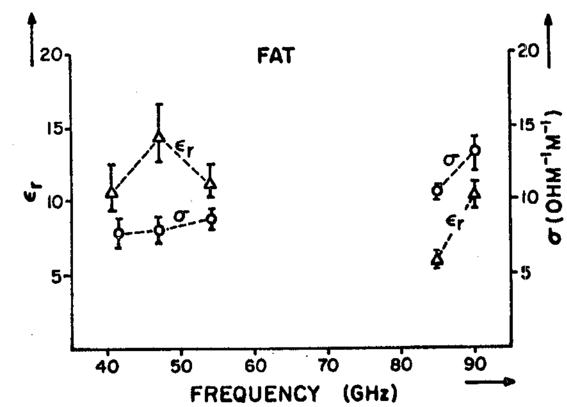

Figure 3a

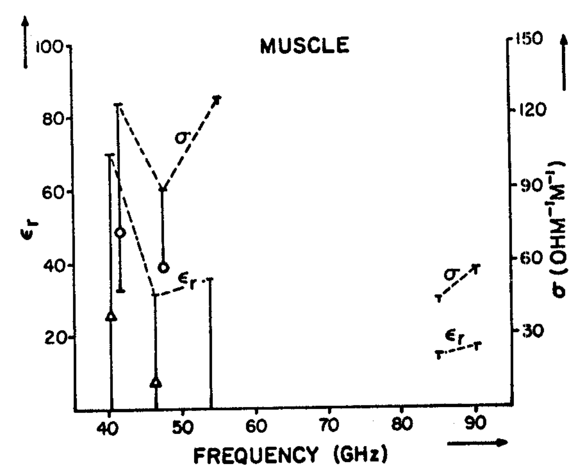

Figure 3b

Figure 3. Conductivity σ and relative dielectric constant ε_r of fat tissue from cattle (Figure 3a) and of muscle tissue from albino Sprague-Dawley CD laboratory rat (Figure 3b) versus frequency. Values in Figure 3b are maximum values.

sus frequency. In the case of muscle tissue (Figure 3b) the experimentally determined value of δ was higher than theoretically possible for the VSWR measured. This indicates substantial multimoding in the samples probably caused by the high value of ε_r and the structural inhomogeneity of the muscle tissue. These values therefore only represent upper limits for ε_r and σ.

It was previously mentioned that a substantial shift in the characteristics of fat was repeatedly and reproducibly measured approximately two hours after the termination of the animal. As an example, the initial dielectric constant ε_r of fat of 8.4 at 47 GHz stayed constant until about 2 hours after termination of the animal; within the next hour it shifted downward to a value of 4.

Thermography tests at 47 GHz show a relatively high emissivitity of the human body indicating small reflections at the skin-free space boundary.[4] However, preliminary arradiation measurements on human skin at the same frequency yielded relatively high reflections. The same effect has been reported for the microwave range around 9.2 GHz.[9] Reflections and temperature gradients in the top skin layers as well as polarization changes are believed to be the reasons for these discrepancies.

Based on these results it appears that millimeter wave irradiation of human body tissue similar to that investigated cannot result in penetration to any significant depth beyond the tissue surface.

References

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