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Complex Permittivity and Penetration Depth of Muscle and Fat Tissues Between 40 and 90 GHz

JOCHEN EDRICH AND PATRICK C. HARDEE

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.**

I. Introduction

The complex permittivity $\varepsilon^* = \varepsilon' - \varepsilon''$ as well as the penetration depth δ of electromagnetic radiation for human and animal skin, muscle, bone, and fat tissues has previously been studied in the microwave region up to approximately 24 GHz [1]–[4]. No published data exist above this frequency. However, the recent expansion of communications and radar into the millimeter wavelength region as well as the exploration of millimeter wave thermography of the human body [5] makes it desirable to determine the electrical properties of certain biological tissues in the frequency range above 24 GHz.

II. Theoretical Considerations

The complex permittivity of structurally well-defined materials with high dielectric constants like ceramics is conventionally determined by measuring the reflection coefficient or by changing the sample length [6]. Both of these methods were found to be unsuitable for the measurement of fresh tissue at the very short millimeter wavelengths. Dimensional variations caused large uncertainties in the angle of the reflection coefficient and therefore unacceptable errors of ε^*. The high values of ε' and ε'' of tissue also require a very short sample length (< 0.5 mm) for the second method which involves a change of the sample length; however, repeated slicing of fresh and therefore soft tissue to this thickness within the required accuracy of about 0.01 mm is very difficult if not impossible.

Therefore only the VSWR values obtained from reflection measurements of tissue could be used. The tissue samples measured were enclosed in a section of standard-height waveguide [7] or placed against the open end of a waveguide [8]. 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 properties could take place. In a third measurement the insertion loss of the same tissue sample enclosed in a waveguide section was determined. Assuming single-mode propagation,

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The authors are with the Department of Electrical Engineering and the Denver Research Institute, University of Denver, Denver, CO 80210.

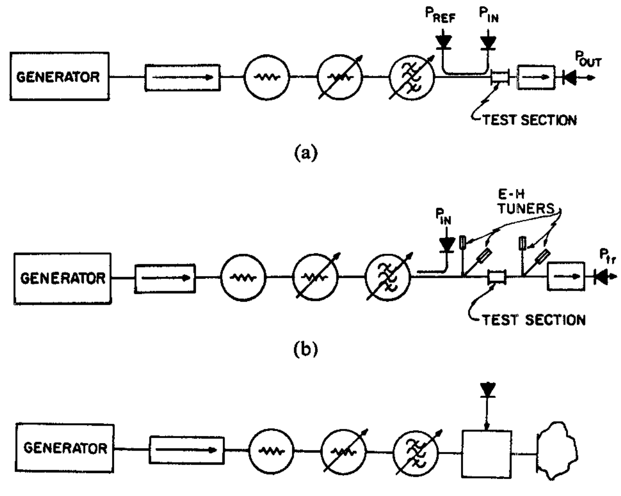

Fig. 1. Reflection and transmission measurement configuration of waveguide-enclosed samples [(a) and (b)] and VSWR measurement using the *in situ* method [(c)].

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, one can express the complex permittivity ε^* and the penetration depth δ of tissue by the following simplified equations [8]:

$$\varepsilon^* = \varepsilon_r\varepsilon_0 - j\sigma/\omega = \mu_0/\bar{Z}^2 + \pi^2/(\omega^2\mu_0{}^2 a) \tag{1}$$

and

$$\delta = c_0(\varepsilon_r{}^2\omega^4 + \sigma^2\omega^2\varepsilon_0{}^{-2})^{-1/4} \sin^{-1} \{0.5 \arctan [\sigma/(\omega\varepsilon_r\varepsilon_0)]\} \tag{2}$$

where c_0, ε_0, and μ_0 represent the velocity of light, the dielectric constant, and the permeability 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 foregoing equation is that multiple reflections within the tissue samples are negligibly small; this assumption is reasonable for high values of ε_r and σ despite the short sample length l (l = 1.5 mm for muscle, and l = 6 mm 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 (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 (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.

III. Experiments

The experimental investigation of the tissue properties was carried out over the two frequency bands 40–54 GHz and 85–90 GHz. Fig. 1 shows the basic setups for the various reflection and transmission measurements. A thin mica window at the tissue sample helped to control the geometry of the tissue and minimize the generation of higher order propagation modes [9].

A jig made out of an opened section of waveguide was used to cut the samples accurately with a slot-guided razor blade (Fig. 2a). Afterwards this waveguide section was covered with a lid and the tissue block pushed against the mica window in the test flange section (Fig. 2b). Special care was taken to obtain a well-

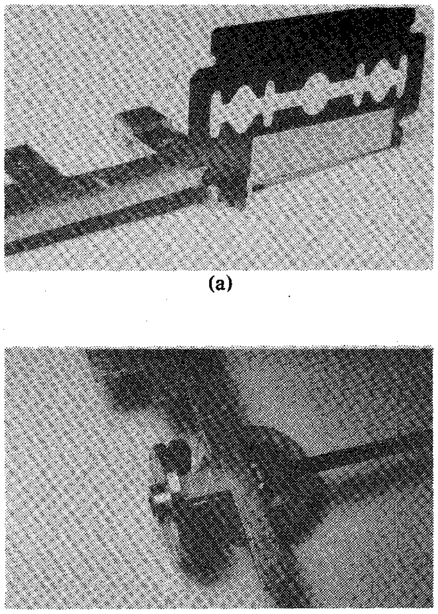

Fig. 2. (a) Shaping of tissue sample using slotted waveguide jig. (b) Inserting sample into the waveguide test section.

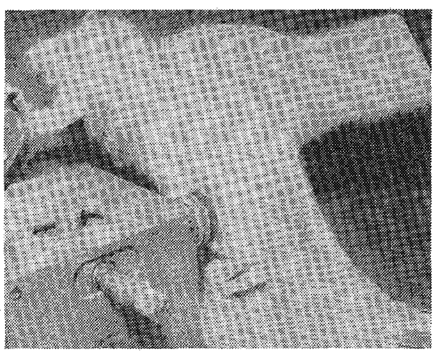

Fig. 3. *In situ* measurement of the reflection coefficient of the thigh muscle of an anesthetized albino Sprague-Dawley CD laboratory rat at 47 GHz.

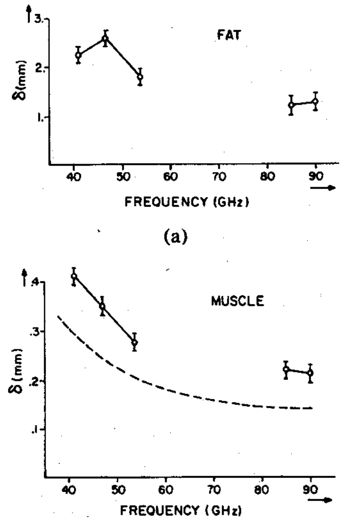

Fig. 4. (a) Measured penetration depth δ versus frequency in fat tissue from cattle. (b) Muscle tissue from albino Sprague-Dawley CD laboratory rat versus frequency. Dashed curve in (b) represents predictions by Schwan and Li [4].

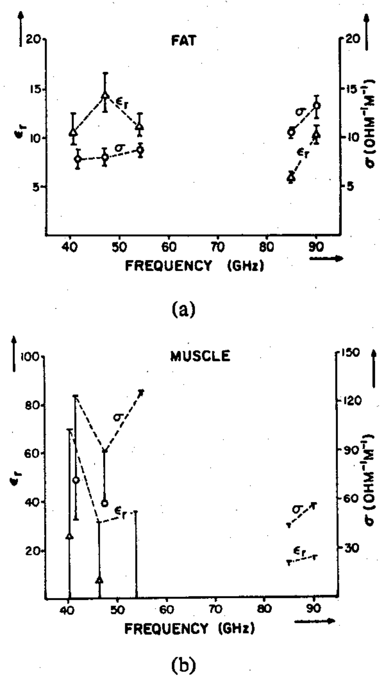

Fig. 5. (a) Conductivity σ and relative dielectric constant ε_r of fat tissue from cattle. (b) Conductivity σ and relative dielectric constant ε_r of muscle tissue from albino Sprague-Dawley CD laboratory rat versus frequency. Values in (b) are maximum values.

defined geometry and to avoid any air enclosures or pockets next to the sample.

One kind of tissue measured was fat obtained from recently slaughtered cattle; it was returned to the laboratory within 55 min of the time the animal was terminated and within 30 min 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 ($\sim$37°C). Small pieces of the specimen (about $\frac{3}{4}$ in cubed) were taken for each separate measurement, held up to the end of the guide, and then discarded.

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 Fig. 3. For the transmission measurements, muscle tissue was excised from the thigh of the rat, inserted in the waveguide, and pressed against the mica window.

Measurements were also taken to determine variations in the measured reflection over a period of time. It was found that between 2 and 3 h 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.

IV. Results and Conclusions

The measured penetration depth δ of fat and muscle is shown in Fig. 4. The curve for muscle exhibits the expected frequency inverse behavior and follows reasonably well the predictions by Schwan and Li [4] based on data measured at lower frequencies. The curve for fat also agrees to within 50 percent of the extrapolated data of England [2].

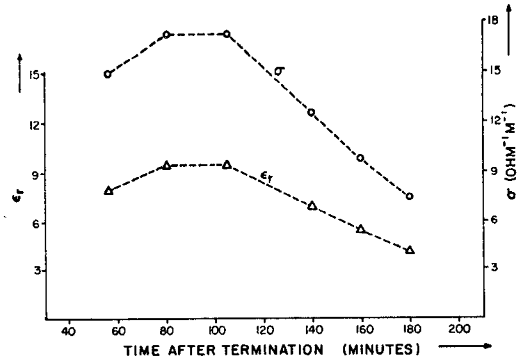

Fig. 6. Change of the maximum possible values of the conductivity σ and the relative dielectric constant ε_r of fat tissue of cattle at 47 GHz as a function of tissue since the termination of the animal.

Using the phaseless technique described in Section III, the relative dielectric constant and the conductivity for the same tissues were determined and plotted in Fig. 5. In the case of muscle tissue (Fig. 5b) the experimentally determined value of δ was higher than theoretically possible for the VSWR measured. This indicates substantial multimoding in the samples caused by the high values of ε_r and the structural inhomogeneity of the muscle tissue. These values therefore only represent upper limits for ε_r and δ.

It was previously mentioned that a substantial shift in the characteristics of fat was repeatedly and reproducibly measured approximately 1.5 h after the termination of the animal. As an example, Fig. 6 shows that the initial values of $\varepsilon_r = 8.4$ and $\sigma = 15\ \Omega^{-1}\ \mathrm{m}^{-1}$ increased slightly until about 1.5 h after termination; within the next 1.5 h they shifted downward to $\varepsilon_r = 4$ and $\sigma = 7\ \Omega^{-1}\ \mathrm{m}^{-1}$. It is interesting to note that this shift did not seem to be affected by the temperature, i.e., the same shifts were observed whether the samples were maintained at a body temperature of approximately 37°C or were allowed to cool down naturally to about 20°C.

Thermography tests at 47 GHz as well as at 9.2 GHz [10] show a relatively high emissivity of the human body indicating that the various skin layers are acting as matching media which was recently confirmed in irradiation tests of human skin in the frequency range between 8 and 95 GHz [11].

Based on these results, it appears that millimeter wave irradiation of human body tissue similar to that investigated has to be considered for microwave hazard studies. The relatively large values of δ for fat of several millimeters around 50 GHz in conjunction with the good match of the skin–air interface and the good temperature and spatial resolution make this range attractive for millimeter wave thermography [5].

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