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DETERMINATION OF THE COEFFICIENT OF REFLECTION FOR MULTILAYERED SYSTEMS OF BIOLOGICAL TISSUES IN THE MICROWAVE RANGE

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ABSTRACT

The coincidence of the results of experimental measurements of the coefficient of reflection with calculated data showed the feasibility of the practical use of analytic and graphic-analytic methods of calculation. A graphic-analytic method is preferred because of its simplicity and visualizability. We can take 50% as the average value of the energy reflected from the body surface for frequencies that are applicable in medicine (the microwave range of 460-2375 MHz). Depending upon the individual characteristics in ths kin and fat thicknesses, at 460 MHz this magnitude can vary within the limits of 35-63%, and 2375 MHz, withingthe limits of 25-76%. A quarter-wave matching layer (for example, a 1 cm thick Mycalex plate) significantly increases the percentage of energy absorbed by the body tissues during microwave therapy in the 12 cm range.

DETERMINATION OF THE COEFFICIENT OF REFLECTION FOR MULTILAYERED SYSTEMS OF BIOLOGICAL TISSUES IN THE MICROWAVE RANGE

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When microwave therapy is used in practice the dosimetry is conducted from the output power of the generator. For a more accurate estimate of the power absorbed by body tissues we must introduce a correction that considers the incomplete absorption of energy by an electromagnetic field.

In calculating and designing medical and experimental high-frequency equipment we must know the load parameters, i.e., the input resistance of the irradiated objects, for a rational selection of the generator operating regime and for agreement of the generator with the emitter.

Disturbance of the uniformity of the medium in which an electromagnetic wave propagates leads to reflection of energy and to the appearance of a wave that propagates in the reverse direction. This phenomenon can be qualitatively characterized by the coefficient of reflection, which is equal to the ratio of the vectors of the reflected and incident waves.

Works [3, 7] calculated the coefficient of reflection for a system consisting of 1, 2 and 3 parallel layers of biological tissues with a plane homogenous wave striking perpendicular to it. These calculations were based on the use of the Maxwell equations for the distribution of an electromagnetic wave in a free space and in tissue layers under satisfactory conditions of the discontinuity of the tangential component of the electrical and magnetic vectors on the boundaries of the tissue layers. These calculations also used experimentally determined electrical parameters of tissue, skin, muscle and fat. However, in connection with the awkwardness of the calculations for determining the input resistance of a multilayered tissue system, these calculations were conducted only for one mutual positioning of tissues (skin-fat-muscle) for several thicknesses of the layers and several points in the frequency range.

Since there are no literary data about an experimental determination of the coefficient of reflection for both separate biological tissues and multilayered systems of tissues, we developed a method for such measurements.

As it is known, the Maxwell equations have an identical form for both a plane homogenous wave that propagates in a free space and the basic type of wave (TEM) in a coaxial line. In connection with this, for the measurements we used a coaxial line filled with tissues. Measurements with a coaxial line have a number of advantageous over measurements in a free space: the absence of outside noises, the small amount of biological material, the simplicity of the method for determining the absolute value and the phase of the coefficient, and the possibility of thermostating the sample. Waveguide lines are less convenient than coaxial lines because of their small range and the large sample volume

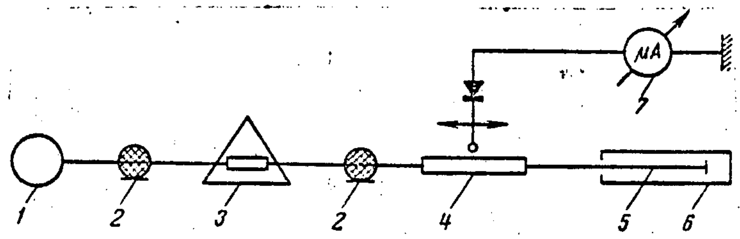

Fig. 1. Diagram of the device for measuring the coefficient of reflection of biological tissues (explanation in the text).

Figure 1 shows the schematic of the measuring device. As the hf source we used one of the following generators [1]: GSS-12 (100-1000 MHz), GSS-15 (1000-2000 MHz) and GS-22 (2000-3000 MHz). The coefficient of reflection of the load, which was a shorted section of coaxial line filled with tissues, was determined with a measuring line (4), which was connected to the generator by a flexible coaxial cable (2) through an attenuator (3) with a 20 dB attenuation. From the microammeter (7) readings we determined the standing-wave ratio (swr) in the line. The modulus of the coefficient of reflection was calculated from the formula:

$$G = \frac{swr - 1}{swr + 1}.$$

The phase of the coefficient of reflection was determined by measuring the distance X_{min} between the surface of the tissues and the first minimum of the standing wave in the line:

$$\phi = \frac{2\pi}{\lambda} \cdot X_{min}$$

As the biological tissues we used the ruminating muscles of a big-horned cow and pig fat. The tissues were thawed from the frozen state at room temperature. To maintain a constant temperature (37 ± 1°) a section of the line with a sample was placed in the thermostat [6].

In accordance with the distribution of layers of tissues in the human body (fat-muscle), the shorted section of the line was filled with the corresponding tissues in this sequence. Since the thickness of muscular tissue in the body for an incident wave is "infinitely" large, the length of the section of the muscle-filled line was so great (9 cm) that we could disregard the wave reflected from the shorted end of the line. The measurements were conducted at a fat-layer thickness of from 0.3 to 3 cm at intervals of 0.3 cm. The squares of the coefficient of reflection, which correspond to reflected power, calculated from the results of measuring the swr are given on Fig. 2.

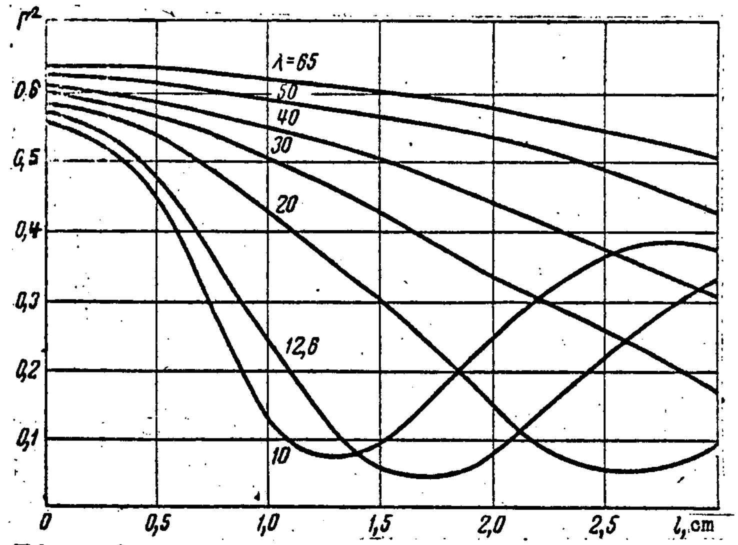

Fig. 2. Dependence of the coefficient of reflection (G_2) (with respect to power) of a two-layer fat-muscle system upon the thickness of the fat layer (ℓ) for wavelengths (λ) from 10 to 65 cm.

The experimental method is inconvenient for determining the coefficient of reflection of a three-layer, let alone a four-layer, system of biological tissues. Since the purely analytical method used by a number of authors is extremely cumbersome, we proposed a graphic-analytic method for calculating the coefficient of reflection of a multilayered system of tissues using an impedance diagram [2]. With this method for wavelengths assigned to medical equipment (65 and 12.6 cm) we determined the coefficient of reflection of a three-layer skin-fat-muscle system. The calculations were conducted for fat-layer thicknesses of 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 cm and for skin thicknesses of 0.2 and 0.4 cm.

To calculate from the diagram we must know the magnitude of the wave impedance $\overline{Z}_\varepsilon = Z_\varepsilon \cdot e^{i\Theta}$, and also the wavelength λ_ε in the medium that is filled with the corresponding tissue.

The real and imaginary part of the impedance, and also its modulus, were determined in the following manner:

Since $\overline{Z}_\varepsilon = R + iX = \frac{377}{\sqrt{\varepsilon}}$, $Z_\varepsilon = \frac{377}{\sqrt{\sqrt{(\varepsilon')^2 + (\varepsilon'')^2}}}$, $R = Z_\varepsilon \cdot \cos\Theta$, $X = Z_\varepsilon \cdot \sin\Theta$, $\Theta = \frac{1}{2}\operatorname{arc\,tg}\frac{\varepsilon''}{\varepsilon'}$, where $\bar{\varepsilon} = \varepsilon' - i\varepsilon''$ is the complex dielectric constant of the tissue.

The wavelength λ_ε was determined from the expression for the coefficient of the phase β_ε of the propagating wave:

$$\lambda_\varepsilon = \frac{2\pi}{\beta_\varepsilon},$$

where

$$\beta_\varepsilon \frac{2\pi}{\lambda} \sqrt{\sqrt{(\varepsilon')^2 + (\varepsilon'')^2} \cdot \cos\Theta}.$$

The results of calculations for muscle, fat and skin at wavelengths of 65 and 12.6 cm are given in the table. In these calculations we used magnitudes of $\bar{\varepsilon}$ (averaged) that were experimentally obtained by a number of authors [1, 5, 6].

Calculated wave impedance and wavelength parameters for certain biological tissues.

Tissue	λ=12,6 cm					λ=65 cm				
	Z_ε (Ω)	R (Ω)	X (Ω)	Θ rad	λ_ε cm	Z_ε (Ω)	R (Ω)	X (Ω)	Θ rad	λ_ε cm
Muscle	52,5	52	8	0,155	1,7	44	41,5	14,7	0,34	8,1
Skin	56,6	55,4	9,6	0,172	1,9	52,5	49,5	16,7	0,318	9,5
Fat	186	184	22,3	0,122	6,4	170	163	44	0,264	30,5

Let us consider an example of calculation from the impedance diagram (Fig. 3) of the coefficient of reflection at a frequency of 460 MHz for a three-layer system at a fat thickness of 1 cm and a skin thickness of 0.2 cm. The tissue arrangement diagram is shown on Fig. 4.

At Point 2 the input impedance of the medium filled with a semi-infinite layer of muscular tissue (the origin at Point 1, see Fig. 4) is the load for the medium filled with fat tissue. Consequently, to plot Point 2 on the diagram we must relate the diagram to a medium that is filled with fat, i.e., one that has the wave impedance $\bar{Z}_f$, and find the point where the standardized impedance is:

$$\bar{Z}_2 = \frac{R_1}{Z_f} + i \cdot \frac{X_1}{Z_f} = 0,25 + 0,09i,$$

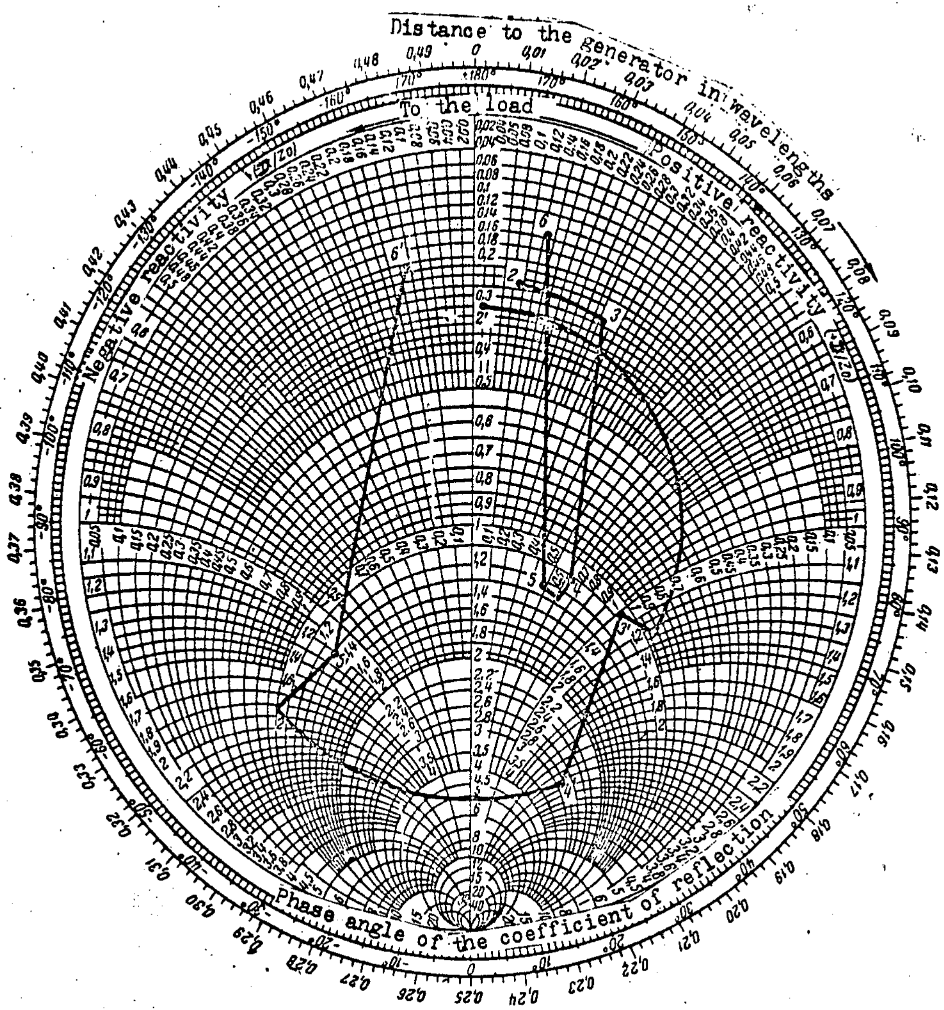

Fig. 3. Calculation (from the impedance diagram) of the coefficient of reflection of a three-layer skin-fat-muscle system when the fat layer is 1 cm thick and the skin is 0.2 cm thick: 1-6 – wavelength of 65 cm; 1^1-6^1 – wavelength of 12.6 cm.

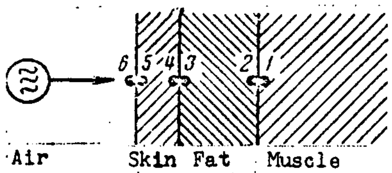

Fig. 4. Diagram of the arrangement of tissue layers in the three-layer skin-fat-muscle system.

We shall disregard the small losses in the fat tissue and consider that the wave impedance of the fat-filled medium is a purely real magnitude, equal to its modulus. There is partial reflection of the incident energy at Point 2. The modulus and phase of the coefficient of reflection on the fat-muscle boundary can be determined directly from the diagram $\overline{G}_2 = 0.6 \cdot e^{0.16i}$. To keep the diagram clear, we have not shown the family of concentric circles that represent the modulus of the coefficient of reflection on it. The magnitude of the modulus is determined as part of the radius of the external circle on the diagram, whose full value corresponds to G = 1.

To go from Point 2 to Point 3 we must move 1 cm, which corresponds to 0.033 λ_f. We get to Point 3 by moving along a line with constant G. The impedance determined by Point 3 is the load for a medium filled with skin. To plot Point 4 on the diagram, we must relate the diagram to a medium filled with skin, i.e., one that has a wave impedance $\overline{Z}_s$, and find the point where the standardized impedance is

$$\overline{Z}_4 = \frac{\overline{Z}_3 \cdot Z_f}{\overline{Z}_s}.$$

Since the losses in skin are relatively great, we cannot disregard them and we must consider the wave impedance Z_s. Therefore, in determining Z_4 we must calculate the modulus

$$Z_4 = \frac{Z_3 \cdot Z_f}{Z_s}$$

and the phase angle $\phi_4 = \phi_3 - \Theta_s$ separately.

To go from Point 4 to Point 5 we must move 0.2 cm, which corresponds to 0.021 λ_s. On the diagram we first move 0.021 λ_s along a circle with constant G. To calculate the attenuation in the skin layer we must determine the change in the coefficient of reflection that occurs. As is known, the modulus of the coefficient of reflection when a wave propagates in a medium with losses (from Point 4 to Point 5) varies according to the following law:

$$\overline{G}_5 = \overline{G}_4 \cdot e^{-2\alpha \cdot \Delta l},$$

where α is the attenuation factor of skin, $\Delta \ell$ is the distance (in cm) between Points 4 and 5.

Having first determined G_4 from the diagram, let us then find G_5. To plot Point 6 on the diagram, we must relate the diagram to the free space that has a wave impedance of 377 cm. The normalized impedance for Point 6 is determined as:

$$Z_6 = \frac{Z_5 \cdot \overline{Z}_s}{377}.$$

Having plotted Point 6 on the diagram, let us determine the sought modulus of the coefficient of reflection on the air-skin boundary, $G_6 = 0.77$. Calculations for other tissue thicknesses are conducted analogously. The obtained values of the coefficient of reflection (with respect to power) are given as graphs on Fig. 5.

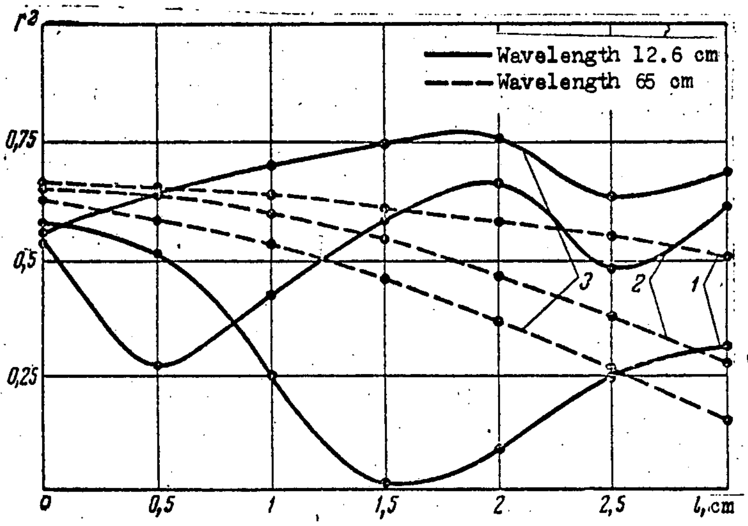

Fig. 5. Dependence of the coefficient of reflection of a three-layered skin-fat-muscle system upon the thickness of the fat layer for skin thicknesses of 0.2 cm (1) and 0.4 cm (2), and without skin (3).

The coinciding results of experimental measurements and the graphic-analytic calculation show that for a two-layer fat-muscle system the coefficient of reflection during irradiation from air depends upon the thickness of the fat differently at different frequencies. At 460 MHz the magnitude of reflected energy smoothly decreases from 64 to 50% when the fat thickness is increased from 0 to 3 cm. At 2375 MHz the reflected energy decreases from 56 to 1.6% when the fat thickness is increased from 0 to 1.5 cm. When the fat thickness is increased further up to 3 cm the reflected energy increases up to 28%. The significant difference in the dependence of the reflected energy upon fat thickness is explained by the fact that at 2375 MHz the fat thickness is commensurate with the wavelength in the tissue (the wavelength in fat is 6.4 cm). At a fat thickness of about 1.5 cm it acts as a quarter-wave transformer, and the impedances of muscular tissue and a free space agree almost completely. This results because at 3 cm only 1/10 of the wavelength accumulates in the depth of the fat tissue.

In calculating the effect of skin up to 0.4 cm thick at 460 MHz the law of the change in the coefficient of reflection with fat thickness does not vary. As in the twc-layer system, as the fat thickness is increased from 0 to 3 cm the coefficient of reflection decreases monotonically. The presence of skin leads to the decrease in the coefficient of reflection being expressed more sharply (in comparison with the two-layer system), and the thicker the skin layer, the sharper the decrease. At ordinary tissue thicknesses (skin, from 0.2 to 0.4 cm; fat, from 0.5 to 2 cm) the energy reflected from the body varied from 63 to 35%, i.e., by a factor of 1.8.

As 2375 MHz the presence of skin leads to an increase in the coefficient of reflection at almost all fat thicknesses, and the thicker the skin layer, the sharper this increase. The greatest increase in the coefficient of reflection occurred at a fat thickness of 1.5 cm and a skin thickness of 0.4 cm. This is explained by the fact that both skin and fat act as quarter-wave transformers in this case. The fat matches the input impedance of muscle with the impedance of a free space, but the skin causes a great mismatch in these conditions.

Thus, at 2375 MHz for ordinary tissue thicknesses (skin, from 0.2 to 0.4 cm, fat, from 0.5 to 2 cm) the energy reflected from the body varies from 25 to 76%, i.e., by 3 times. In comparison with the reading at 460 MHz, this change has increased by 1.7 times.

The smaller range of change in the coefficient of reflection is a significant advantage for decimeter waves. Thanks to this we can guarantee sufficiently accurate (from the standpoint of absorbed power) reproduction of the procedural conditions for remote irradiation if we fix all the characteristics: the emitter, the gap size and the output power. The difference in the absorbed power due to differences in the coefficient of reflection of the body does not exceed 20%. But for microwaves with a wavelength of 12.6 cm this difference can exceed 50%.

The smaller spread of the coefficient of reflection for decimeter waves has another significant importance. The small effect of the skin and fat thicknesses on the coefficient of reflection indicates that for decimeter waves these tissue layers do not have a significant effect on the distribution of the field in front of the tissues and, consequently, in the tissue layers. Thus, we can say that in the decimeter range there are no noticeable standing waves in the skin and fat layers, which precludes the possibility of their local overheating.

With the aid of the circular diagram of the full impedances we solved the problem (which is practically important for physiotherapy) of the use of matched layers to reduce the reflection of energy by biological tissues.

Work [4] proposed placing a 1 cm thick Mycalex plate on the irradiated surface of the body during microwave therapy. The idea is that the plate of Mycalex, which has a dielectric constant of $\varepsilon = 6$, is a quarter-wave transformer that matches the wave impedances of muscle ($\varepsilon \gtrsim 50$) and a free space. Despite the fact that these discussions were supported by experimental data, this proposal encountered serious objections from some authors [8], who indicate that in the presence of a quarter-wave layer of fat, which is also such a transformer, a Mycalex plate significantly worsens the match of the body with a free space.

We propose that the divergence between experimental results and the theoretical examination can be explained by the fact that in the latter case the role of the skin is not considered. We conducted experimental measurements and a graphic-analytic calculation to explain the existing contradiction.

We used the method described above for the measurements. We placed a Mycalex washer in a section of shorted coaxial line in front of a three-layer system of tissue. We examined the most interesting case from the standpoint of the mismatching effect of Mycalex: fat thickness, 1.5 cm; skin thickness, 0.2 and 0.4 cm. For the 12.6 cm wavelength we conducted a graphic-analytic calculation of a three-layer system of tissue with Mycalex. The calculation was conducted for fat thicknesses of 1, 2 and 3 cm at skin thicknesses of 0.2 and 0.4 cm, and also for a two-layer system (without skin).

The results of measurement and the calculation of the coefficient of reflection of a three-layer system of tissues with a quarter-wave matching layer showed that at all fat thicknesses the Mycalex increases the absorption of energy incident to the body. Despite the fact that at a fat thickness corresponding to 1 quarter of the wavelength Mycalex would significantly improve the matching, the presence of skin leads to the opposite effect. At a skin thickness of 0.2 cm a quarter-wave layer of Mycalex reduces the percentage of reflected energy by 2.9 times at a fat thickness of 1.5 cm, and 12 times at a fat thickness of 3 cm; at a skin thickness of 0.4 cm the reductions are 4.7 times at a fat thickness of 1.5 cm and 3.8 times at a fat thickness of 3 cm.

Because of the great thickness of the matching layer, which must correspond to a quarter of the wavelength, this method is inapplicable at 460 cm.

Conclusions

1. The coincidence of the results of experimental measurements of the coefficient of reflection with calculated data showed the feasibility of the practical use of analytic and graphic-analytic methods of calculation. A graphic-analytic method is preferred because of its simplicity and visualizability.

2. We can take 50% as the average value of the energy reflected from the body surface for frequencies that are applicable in medicine (the microwave range of 460-2375 MHz). Depending upon the individual characteristics in the skin and fat thicknesses, at 460 MHz this magnitude can vary within the limits of 35-63%, and at 2375 MHz, within the limits of 25-76%.

3. A quarter-wave matching layer (for example, a 1 cm thick Mycalex plate) significantly increases the percentage of energy absorbed by the body tissues during microwave therapy in the 12 cm range.

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