Dielectric Properties of Glucose Solutions in the Millimeter-Wave Range and Control of Glucose Content in Blood

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ABSTRACT. Investigations of the dielectric properties of sugar solutions, as well as blood imitators and blood, in the millimeter-wave range allow one to obtain valuable information on the possibility of real-time control of glucose concentration in blood using electromagnetic waves in the millimeter-wave ranges. These investigations are also of interest for other applications.

Introduction

To determine the complex permittivity, $\varepsilon = \varepsilon' + i\varepsilon''$ of a medium using noninvasive methods, one has to measure two parameters of the reflected electromagnetic wave. Usually (see, for example, [1]), one employs a sophisticated and expensive vector network analyzers and measures the modulus, $|r|^2$, and phase, φ, of the reflection coefficient, $R^* = |r|^2 e^{i\varphi}$ ($|r|^2$ is the power reflection coefficient and $i = \sqrt{-1}$). However the measurement of the phase of the reflection coefficient is a rather difficult problem, and the measurement error amounts to ± 5%. For this reason, common measurement techniques cannot be applied to the noninvasive determination of small concentrations of glucose in water. Here, we use a sufficiently simple scheme for determining ε' and ε'' of a medium, which consists in measuring the modulus, $|r_{min}|^2 = R_{min}$, and frequency, f_{min}, of a millimeter wave (f_{min}, corresponds to the minimum of the reflection coefficient R_{min},) from the following structure: a plane-parallel matching plate made of a low-loss dielectric – a medium under measurement with high losses. We developed computer programs to calculate the dielectric properties of the medium under test from the measured $|r_{min}|^2$ and f_{min}, and experimental setups.

Measurement Method

To determine the real ε' and imaginary ε'' parts of the complex permittivity of a medium under test, we used a simple scheme consisting in measuring the modulus, $|r_{min}|^2 = R_{min}$, and frequency, f_{min}, of MM waves corresponding to the minimum of the reflection coefficient from the following structure: a plane-parallel matching plate made of a low-loss dielectric – a medium under test with high losses. Figure1 shows the change of power reflection coefficients of two media with different ε against the frequency of the incident millimeter wave. We can calculate $\varepsilon'_{m,\chi}$ and $\varepsilon''_{m,\chi}$ from $R_{min,\chi}$ and $f_{min,\chi}$ using expression for the reflection coefficient $r^{\bullet}$ from such structure [2].

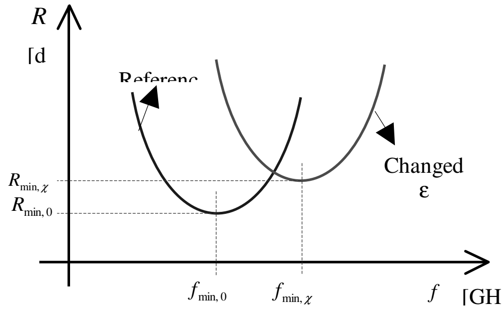

Fig. 1. The power reflection coefficients of two media (a reference medium and a medium with χ% of glucose) versus the frequency of the incident MM wave.

Experimental Setup and Measurements of Solutions

The measuring setup based on SWR and attenuation panoramic meters. Using this setup we carried out measurements of the properties of glucose solutions in water and blood imitators (physiological solution: 0.9% NaCl in water) in the millimeter wave band for small glucose concentrations W from 5 to 0.25% wt.

The main conclusions of these measurements are as follows:

1. The dielectric properties of glucose solutions in water and in a solution of NaCl in water are measured for the first time in a wide range of frequencies from 10 to 93 GHz for glucose concentrations of W ≤ 5% wt.
2. It is established that, for frequencies below 80 GHz, the values of ε' and ε'' for 0.9% NaCl are less than those for water. In the frequency interval from 80 to 93 GHz, this difference substantially

decreases. whereas ε'' in our experiments is substantially greater than that in [9].

. Investigation of Blood

These experiments were carried out in a thermostatically controlled chamber when a drop of blood taken immediately from the fingertip of a test person was placed on a matching plate. The measurements were carried out with a waveguide of cross section 5.2 × 2.6 mm (operating frequencies 41- 42 GHz), which was completely covered by a drop of blood. We determined ε' and ε'' of blood at temperatures close to the temperature of a human body. At $f = 42.93$ GHz, $\varepsilon' = 18.1 \pm 0.2$ and $\varepsilon'' = 23.8 \pm 0.2$; i.e., the difference between ε' and ε'' for different persons was small. Note that the data on ε' and ε'' of blood (not *in vivo*) that are available in the only publication [3] (which were measured at 25°C: $\varepsilon' = 13 \pm 3$ and $\varepsilon'' = 20 \pm 3$) are in agreement with our data if we introduce temperature corrections by analogy with the temperature dependence for permittivity of water.

Investigation of Skin

From the electrodynamical point of view, skin and adjoining blood-filled tissues represent a much more complicated object of study than blood. Many authors (see, for example, [4]) pointed out that the parameters of skin, such as thickness, blood richness, sweat, and moisture, depend on a test person, his age, and a place on his body. Moreover, the blood richness and moisture depend on external factors, such as temperature, humidity, and illumination, and internal factors, such as physical and intellectual stresses and a general state of health Therefore, at the first stage, we measured $R_{\min}$ and $f_{\min}$ for different parts of body at different frequencies. As was expected, fingertips, palms, wrists, forearms, and earlobes have substantially different values of the reflection coefficient. When we used the matching plates that guaranteed a deep minimum $R_{\min}$ for water and blood, the maximum reflection $R_{\min}$ (the minimal value of | $R_{\min}$|) was attained with fingertips and palms. The best matching was achieved for earlobes and forearms. Therefore, further measurements of $R_{\min}$ were carried out on forearms. ε' and ε''' monotonically decrease as frequency increases. Note that these values of ε' at frequencies 30 - 40 GHz are in satisfactory agreement with the results of [4], whereas ε'' in our experiments is substantially greater than that in [4].

The penetration depth d of the wave into the skin equals approximately $3/\alpha$ (α is absorption coefficient) and ranges from 0.7 mm for 30 GHz to 0.36 mm for 77 GHz at 36 - 37°C.

As for the measurements of $R_{\min}$ and $f_{\min}$ as a function of W, just as in the case of measurements of blood at a frequency of 43 GHz, we observed a correlation between $R_{\min}$ and W as W increased after taking glucose on an empty stomach.

Conclusions

A new method has been applied to measure the dielectric properties of glucose solutions in water and in a blood imitator. The measurements have been carried out for the first time in the frequency range from 28 to 93 GHz for glucose concentrations *W* ranging from 5 to 0.5%. to 0.04% wt. (2 mmoles/l).. These results may serve a basis for the design of a laboratory or industrial equipment for controlling small concentrations of glucose (sugar) in water and in the physiological solution.

The dielectric properties of fresh blood are measured for the first time at frequencies 42 and 66 GHz. The method developed in the project allows a real-time determination of glucose content in blood using a single drop of blood.

. As for the noninvasive determination of the glucose concentration W, we obtained a good correlation between W and the output MM wave signal of a device that was in contact with skin in the case where W increases after taking glucose on an empty stomach.

References

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