

Dielectric Properties of Water Solutions with Small Content of Sugar and Glucose in the Millimeter Wave Band and the Determination of Glucose 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 such as, for example, wine industry, determination of water content in oil, oil products, and other liquids.

Keywords: Dielectrics, solutions, blood, skin, millimeter, waves

1 Introduction

To determine the complex permittivity, i.e., ϵ' and ϵ'' 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 $\pm 5\%$. 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 (MM) 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.

2 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 (water, solutions, blood, and human skin). Figure 1 shows the power reflection coefficients of two media (e.g., a reference medium (water) and a water with $\chi\%$ of glucose) against the frequency of the incident MM wave. In Fig. 1, $R_{min,0}$ and $f_{min,0}$ represent the minimal power reflection coefficient and the corresponding frequency of the reference medium (pure water). When $\chi\%$ of glucose is added to the reference medium, one can see the power reflection coefficient and the corresponding frequency shift from $R_{min,0}$ and $f_{min,0}$ to $R_{min,\chi}$ and $f_{min,\chi}$, respectively. We can calculate $\epsilon'_{m,\chi}$ and $\epsilon''_{m,\chi}$ from $R_{min,\chi}$ and $f_{min,\chi}$ using well-known expression (1) for the reflection coefficient r from such structure [2]:

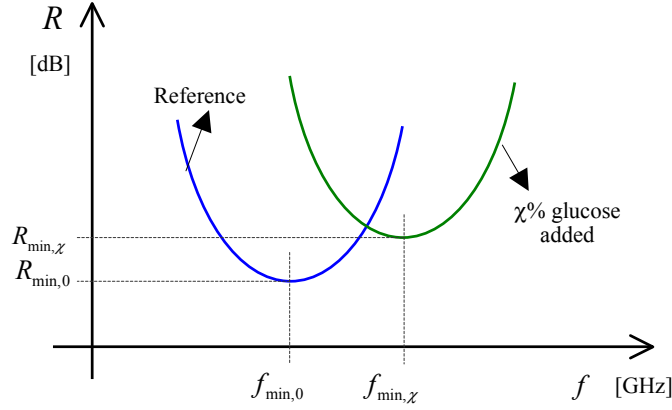


Fig. 1 The power reflection coefficients of two media (a reference medium and a medium with $\chi\%$ of glucose) versus the frequency of the incident MM wave.

Two types of measurement methods have been developed for the frequency range from 30 to 100 GHz. The first one is a waveguide method (WM) in which a plane-parallel matching plate is inserted into a single-mode rectangular waveguide with H_{10} mode. The second is a quasi-optical method (QM) in which the plane-parallel plate is placed between a horn and the media under test. For the plates available, $|r_{\min,0}^*|^2$ for structures with pure water was measured to be less than -20dB. The values of ϵ'_w and ϵ''_w of pure water needed for calculation were borrowed from [3]

$$r^* = \frac{\left(\frac{1-n_p^*}{1+n_p^*}\right) + \left(\frac{n_p^* - n_m^*}{n_p^* + n_m^*}\right) \exp[2i\beta^* l_p]}{1 + \left(\frac{1-n_p^*}{1+n_p^*}\right) \left(\frac{n_p^* - n_m^*}{n_p^* + n_m^*}\right) \exp[2i\beta^* l_p]} \quad (1)$$

Here, n_m^* is the complex refractive index of the medium under test and n_p^* and l_p are the complex refractive index and the thickness of the plane-parallel matching plate. ϵ' , ϵ'' and n , k are related by the formulas

$$\epsilon' = n^2 + iK^2, \quad \epsilon'' = 2nK. \quad (2)$$

β^* is the propagation wavenumber given by

$$\beta^* = \frac{2\pi}{\lambda_0} n_p^* = \frac{2\pi f}{c} n_p^* = \frac{2\pi f}{c} (n_p + iK_p). \quad (3)$$

Here, λ_0 and c are the free-space wavelength and the speed of light in free-space, respectively. If the reflection coefficient in Eq. (1) is zero at given frequency $f_{\min,0}$, the thickness, l_p , and the refractive index, n_p , of the plane-parallel matching plate must be

$$n_p = \left(n_m + \frac{K_m^2}{n_m - 1} \right)^{1/2} \quad (4)$$

$$l_p = \frac{(2s+1) \cdot c}{4n_p f_{\min,0}} - \arctan\left(\frac{2n_p \kappa_m}{n_m^2 + \kappa_m^2 - n_p^2}\right) \frac{c}{4\pi n_p f_{\min,0}} \quad (5)$$

Here, s is an integer, $s = 0, 1, 2, \dots$

3 Experimental Setup and Measurements of Solutions

The measuring setup based on SWR and attenuation panoramic meters is shown in Fig. 2.

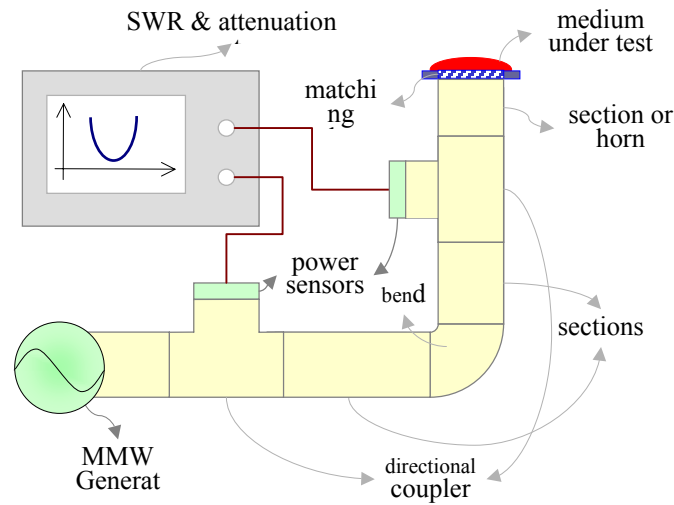


Fig. 2 Schematic diagram of the experiment set up.

Using the setup shown in Fig. 2, 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. Some measurement results obtained in the frequency range from 9 to 93 GHz are shown in Tables 1 and 2.

Our measurements have shown that the values of ϵ'_w and ϵ''_w are in good agreement with the results of [3, 7].

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 $W \leq 5\%$ 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, the difference between these values substantially decreases.
3. Depending on the glucose concentration W in water up to $W = 5\%$, one observes a decrease in ϵ' and ϵ'' in the entire range of frequencies except for frequencies of 92- 93 GHz, where the values of ϵ'' slightly increase as W increases.

Table 1 Dielectric properties of glucose solutions in water at frequencies 9,3 - 92,7 GHz.

ϵ', ϵ''	9,3 GHz	28,1 GHz	31,3 GHz	37,0 GHz	42,7 GHz	48,1 GHz	62,6 GHz	77,4 GHz	83,5 GHz	92,7 GHz
ϵ'_w	60,7	24,3	21,8	18,4	14,6	14,5	10,8	8,63	8,29	7,78
$\epsilon'_{0,5}$	60,4	23,8	21,8	18,1	14,4	14,4	10,7	8,53	8,19	7,76
ϵ'_3	58,3	23,0	21,6	16,2	14,0	14,0	10,4	8,28	7,60	7,55
ϵ''_e	34,0	31,5	31,0	27,8	24,8	24,8	18,9	15,21	14,02	13,13
$\epsilon''_{0,5}$	33,8	30,7	30,1	27,2	24,6	24,5	18,6	15,15	13,91	13,05
ϵ''_3	32,9	30,2	29,4	26,3	23,7	23,7	17,9	14,58	13,39	13,32
T, °C	18	18	19	19	17,5	17,5	20	18	19	19

Table 2 Dielectric properties of glucose solution in 0.9% NaCl at frequencies 9,3- 92,7 GHz

ϵ', ϵ''	28,1 GHz	31,3 GHz	37,0 GHz	42,7 GHz	48,1 GHz	62,6 GHz	83,5 GHz	92,7 GHz
ϵ'_ϕ	19,9	23,0	15,1	14,5	14,5	9,35	8,73	7,83
$\epsilon'_{0,5}$	20,0	23,0	14,8	14,4	14,4	9,25	8,29	7,81
ϵ'_3	20,3	22,7	14,4	13,6	13,9	9,16	8,02	7,60
ϵ''_ϕ	31,7	32,0	26,1	25,1	25,0	18,57	14,13	12,94
$\epsilon''_{0,5}$	31,4	31,5	25,8	25,0	24,8	18,51	14,05	12,85
ϵ''_3	29,7	29,7	24,8	23,7	23,7	17,74	13,90	13,30
T, °C	18	17	19	17,5	17,5	20	19	19

4. Note that, in the investigations of Japanese scientists [4,5] of glucose concentrations in physiological solutions in the frequency range 30—40 GHz, the values of ϵ' increased, in contrast to our results, with the glucose concentration, whereas the values of ϵ'' decreased, like in our experiments. The measurements in [4] and [5] showed that the frequency dependence of ϵ' exhibits different behavior. These facts can be attributed to the significant error in measuring the phase by a Vector Network Analyzer, which amounts to at least 5%.

5. The maximum sensitivity of the method for measuring ϵ' and ϵ'' of solutions to the glucose concentration was 2.2 dB / 0.5% wt. in water and 0.9 dB / 0.2% wt. in a physiological solution. The extrapolation of these results allows us to suggest that a sensitivity of about 0.1 dB / 0.04% wt., i.e., of about 2 mmoles /l, can be attained with the plates available.

4 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. Typical results of one of experiments for 4 persons in a thermostatically controlled chamber are shown in Table 3.

Table 3 Investigation of blood

N	Hb, g/l	$T_1; t = 32-34^\circ\text{C}$				$T_1 + 40 \text{ min}; t = 36^\circ\text{C}$				$T_1 + 120 \text{ min}; t = 36-37^\circ\text{C}$			
		W	Ch	R, dB	f, GHz	W	Ch	R, dB	f, GHz	W	Ch	R, dB	f, GHz
1	150	3.9	253	37.4	42.71	6.1	247	39.6	42.74	3.9	253	38.2	42.75
2	142	3.6	332	37.9	42.77	4.3	309	40.5	42.73	3.9	295	38.8	42.75
3	136	3.7	268	39.1	42.74	4.4	265	39.5	42.74	3.6	244	<40	42.77
4	140	3.7	367	39.0	42.74	5.3	355	39.6	42.74	3.9	346	39.6	42.74

Here, W is the content of glucose in mmoles / l, Ch is the content of cholesterol in mg, Hb is the content of hemoglobin in g / l, T_1 is the moment of time when persons 1—4 took 50 g of glucose on an empty stomach.

Thus, the data of Table 3 show the following:

1. The dependence of R on W has an individual character; however, all the persons show a decrease in R after taking glucose.
2. The inverse process of decreasing W , which is recorded by the variation of R , is not so clearly pronounced. This fact can be connected with the physiological processes that take place in blood as the glucose concentration decreases.
3. There is no obvious effect of hemoglobin (which was constant during the measurements).
4. The content of cholesterol, may be responsible for the difference between the functions $R(W)$ measured as W decreases and increases.

We determined ϵ' and ϵ'' of blood at temperatures close to the temperature of a human body. At $f = 42.93 \text{ GHz}$, $\epsilon' = 18.1 \pm 0.2$ and $\epsilon'' = 23.8 \pm 0.2$; 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 [8] (which were measured at 25°C : $\epsilon' = 13 \pm 3$ and $\epsilon'' = 20 \pm 3$) are in agreement with our data if we introduce temperature corrections by analogy with the temperature dependence of ϵ' and ϵ'' of water.

5 Investigation of Skin

From the electrodynamic point of view, skin and adjoining blood-filled tissues represent a much more complicated object of study than blood. Many authors (see, for example, [9]) 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. Just as in [10], where the measurements were carried out in the infrared band, for different persons, we observed different values of R_{\min} and f_{\min} at equal values of glucose concentration. We also found that the values of R_{\min} and f_{\min} depend on the pressure of the matching plate to the forearm and its position on the forearm. To minimize these effects, we carried out systematic measurements in the long-wavelength region of the millimeter-wave band, where, as is well known (see, for example, [9] and our skin data presented in Table 4), the penetration depth of the wave $d \approx 1/\alpha$ (the skin depth) is maximal, and, as a result, the wave interacts with parts of body that are richer in blood.

Table 4 shows that ϵ' and ϵ'' monotonically decrease as frequency increases. The penetration depth d of the wave into the skin equals approximately $1/3\alpha$ and ranges from 0.7 mm for 30 GHz to 0.36 mm for 77 GHz at 36–37°C. These values are close to those of water at the same temperature. The results of Table 4 are obtained by averaging the results of more than 20 measurements at $W = 4$ –5 mmol/l. Note that these values of ϵ' at frequencies 30–40 GHz are in satisfactory agreement with the results of [9], whereas ϵ'' in our experiments is substantially greater than that in [9].

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 (sugar) on an empty stomach. At frequency of about 60 GHz, a variation in R_{\min} was much smaller than that at 42 GHz, which is likely to be attributed to the smaller penetration depth d . Note that, in the afternoon (after 3–4 p.m.), a variation in R_{\min} for close values of W in normal situation (without additional taking glucose) was much greater than that before the noon. This fact indicates to certain physiological changes in skin at the depth d that are associated with vital functions of the organism, such as movements, nourishment, and tiredness, which were also pointed out in [10].

To eliminate the effects of the position and the pressure of the matching plate and

Table 4 Dielectric properties of skin

f, GHz, tan δ , α	29.8	tan δ α	42.6	tan δ α	66	tan δ α	77.4	tan δ α
Water: 37°C	$\epsilon =$ 34.05+i34.3 $m =$ 6.42+i2.67	1.0 14.5	$\epsilon =$ 23.1+i30.5 $m =$ 5.5+i2.8	1.32 21.3	$\epsilon =$ 13.87+i23.29 $m =$ 4.93+i2.67	1.68 30.9	$\epsilon =$ 11.7+i20.7 $m =$ 4.2+i2.5	1.8 34.4
Skin	$\epsilon =$ 13.0+i34.2 $m =$ 4.98+i3.44	2.63 18.7	$\epsilon =$ 10.6+i23.5 $m =$ 4.3+i2.8	2.2 21.4	$\epsilon =$ 7.86+i12.7 $m =$ 3.38+i1.88	1.62 22.9	$\epsilon =$ 7.6+i10.3 $m =$ 3.2+i1.6	1.4 22.4

the above-mentioned physiological phenomena of a person, we carried out repeated measurements of R_{\min} in a modified setup. In this setup, the diameter of the contact area between skin and the measurement plate was increased to 35 mm to reduce the effect of the position of the plate on the skin, the measurements were fulfilled at a fixed frequency near 35 GHz, and the test person took only glucose and was at rest during the whole period of measurements. The results of one experiment are shown in Table 5.

Table 5 Results of W measurements with a non-invasive device

W, mmol/l	4.5	11.0	11.7	10.8	8.5	6.0
T, min	0	3	60	90	120	150
R, - dB	7.2	4.8	4.2	4.2	4.8	7.0

Here, W is the glucose content measured by a standard invasive glucometer, R is the reflection coefficient measured by the MM setup. Table 5 shows a clear correlation between the reflection coefficient R and W .

6 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%. A sensitivity of up to 2.2 dB per 0.5% wt. of glucose concentration was realized. Extrapolation of these results shows that the sensitivity may be increased to 0.04% wt. (2 mmol/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 blood are measured *in vivo* (without preservatives) for the first time with a sufficiently high degree of accuracy (the measurement accuracy of ϵ' and ϵ'' is ± 0.2) at frequencies of 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.

The reflectivity of skin from various parts of human body has been measured at frequency intervals from 30 to 80 GHz. It has been established that, for close values of W , fingertips, on the one hand, and forearms and earlobes, on the other, have substantially different values of R_{\min} and f_{\min} . 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.

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