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Determination of the Optimum Test Conditions for Measurement of Glucose Level in Liquids

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Abstract: Diabetes is a disease that affects more than 400 million people worldwide and currently lacks a cure. Monitoring blood sugar levels is crucial in minimizing the effects of this disease and protecting against its complications. Invasive and minimally invasive methods are commonly used traditional approaches for detecting and monitoring blood sugar levels. However, these methods bring along psychological and infectious risks. Currently, efforts are being made to develop a non-invasive method for determining blood sugar levels. Microwaves offer the possibility of non-invasive glucose measurement as they do not cause any harmful effects on human tissue. Furthermore, the complex permeability of blood is sensitive to glucose concentration in the microwave band. In literature, most of the studies are done with vector network analyzers (VNA) to detect blood sugar level noninvasively. In this study, an expensive and bulky VNA is replaced by an affordable microwave source and RMS power detector. The influence of the type and diameter of the test tube material used for non-invasive determination of sugar levels is examined with this setup. Additionally, the effect of the distance between the Vivaldi antennas used during measurements and the test tube is investigated. The results indicate that measurements performed using plastic test tubes yield better results compared to glass test tubes. Moreover, reducing the diameter of the test tube leads to improved outcomes. It has been observed that accurate results cannot be obtained if the antennas and the test tube are too close (<0.5 cm) or too far (>4.5cm) from each other.

Key words: Microwaves, Non-invasive glucose detection, Glucose detection, Diabetes, Vivaldi antenna

Sıvılarda Glikoz Seviyesinin Ölçülmesi İçin Optimum Test Koşullarının Belirlenmesi

Öz: Diyabet, dünya çapında 400 milyondan fazla insanı etkileyen ve şu anda tedavisi bulunmayan bir hastalıktır. Kan şekerinin takibi bu hastalığın etkilerini en aza indirmek ve komplikasyonlarından korunmak açısından çok önemlidir. İnvaziv ve minimal invaziv yöntemler, kan şekeri seviyelerinin tespiti ve izlenmesinde yaygın olarak kullanılan geleneksel yaklaşımlardır. Ancak bu yöntemler psikolojik ve bulaşıcı riskleri de beraberinde getirmektedir. Şu anda kan şekeri seviyelerini invazif olmayan bir yöntem geliştirerek belirlemek için çaba sarf edilmektedir. Mikrodalgalar insan dokusu üzerinde herhangi bir zararlı etkiye neden olmadığından, invaziv olmayan glikoz ölçümü olanağı sunmaktadır. Ayrıca kanın kompleks geçirgenliği mikrodalga bandındaki glikoz konsantrasyonuna duyarlıdır. Literatürde kan şekeri düzeyinin invazif olmayan bir şekilde tespit edilmesine yönelik çalışmaların çoğu vektör ağ analizörleri (VNA) ile yapılmaktadır. Bu çalışmada pahalı ve hantal bir VNA'nın yerini uygun fiyatlı bir mikrodalga kaynağı ve RMS güç dedektörü almıştır. Bu kurulumla şeker seviyelerinin invaziv olmayan tespiti için kullanılan test tüpü malzemesinin türü ve çapının etkisi incelenir. Ayrıca ölçümler sırasında kullanılan Vivaldi antenleri ile test tüpü arasındaki mesafenin etkisi araştırılmıştır. Sonuçlar, plastik test tüpleri kullanılarak yapılan ölçümlerin cam test tüplerine göre daha iyi sonuçlar verdiğini göstermektedir. Ayrıca test tüpünün çapının azaltılması daha iyi sonuçlara yol açar. Antenlerin ve test tüpünün birbirine çok yakın (<0,5 cm) veya çok uzak (>4,5 cm) olması durumunda doğru sonuçların alınamayacağı görülmüştür.

Anahtar kelimeler: Mikrodalga, İnvazif olmayan glikoz tespiti, Glikoz tespiti, Diyabet, Vivaldi anten

1. Introduction

Diabetes is one of the important chronic diseases characterized by very high sugar levels in the blood [1]. Diabetes occurs when the body cannot produce enough insulin or cannot use insulin effectively. Two hours after eating, the human blood glucose level should ideally remain below 140 mg/dl. Higher levels can, over time, result in significant harm to the heart, blood vessels, eyes, kidneys, and nerves. The incidence of diabetes in the last century is directly related to poor lifestyles such as low physical activity and poor diet. The World Health Organization (WHO) reports that roughly 422 million individuals globally suffer from diabetes in 2023, with most residing in low to middle-income nations. Each year, diabetes is the direct cause of 1.5 million deaths[1]. Given that diabetes can lead to severe damage to vital organs, potentially resulting in life-threatening complications, there must be a continuous and reliable process for monitoring blood sugar levels. Many of the devices in use today require a blood sample and are invasive methods that are often

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painful for patients [2]. In addition, some commercial devices used today offer some solutions for continuous monitoring of blood sugar, but these devices are expensive and short-lived [3]. Machine learning methods are widely used in different fields of medicine, and they can also be used to determine the level of glucose in the blood [4]–[6]. Therefore, cost-effective and non-invasive technology is required for safe and continuous monitoring of blood glucose.

In order to monitor the glucose level in the blood, various researchers propose variety of methods spanning different frequency ranges. Non-invasive methods can be divided into electromagnetic-based and electrochemical-based methods. Many studies have been carried out using electrochemical-based methods [7]–[10]. These studies showed a subtle and delayed relationship between blood glucose levels and measured values. However, it is premature to evaluate the feasibility of these studies. Because the studies are still in their nascent stage [11]. In methods based on electromagnetism, a range of wavelengths within the electromagnetic spectrum are employed. After interaction with the human body, the relationship between the size, phase and frequency of the measured signal and the glucose level in the blood is investigated [2], [12]–[14]. In the last decade, interest in detecting blood glucose levels using microwaves has increased [15]–[19]. The behavior of electromagnetic waves in a material depends on the dielectric properties of the material. These features form the basis of the primary design of the microwave frame [20], [21]. Evaluation of the dielectric properties of blood is of great importance for successful microwave diagnosis and treatment. In recent years, researchers have turned to studying blood glucose dielectric properties to pave the way for non-invasive and microwave band blood glucose monitoring systems. The relationship between microwave absorption and glucose concentration in human blood samples via the complex refractive index has been demonstrated in previous studies [22]–[24]. In recent times, artificial intelligence methods have gained popularity for assessing glucose concentrations in blood samples [25]–[27].

The present work seeks to pave the way for monitoring blood glucose levels using the vivaldi antenna at 5.5 GHz as a microwave sensor. In this study, an expensive and bulky VNA was replaced with an affordable microwave source and RMS power detector. The effect of the type and diameter of the test tube material used for the non-invasive determination of sugar levels is examined with this setup. In addition, the effect of the distance between the Vivaldi antennas used during the measurements and the test tube was examined. The primary advancement offered by the study presented here is the elimination of the need for costly equipment like a VNA to serve as a signal generator within the proposed experimental framework. Additionally, this research lays the groundwork by establishing the most favorable test conditions, setting a benchmark for similar studies in the literature.

2. Material and Methods

2.1. S-Parameters

Two-port S parameters are established by considering the propagation of waves along transmission lines with actual characteristic impedance Z_0 connected to each of the network's ports, as illustrated in Figure 1 [28].

Figure 1. Illustration of a two-port circuit

$$V_1^- = S_{11}V_1^+ + S_{12}V_2^+,\ V_2^- = S_{21}V_1^+ + S_{22}V_2^+ \quad (1)$$

where S_{ij} are the individual S parameters. The equations mentioned above are represented in matrix form as follows,

$$\begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix} \quad (2)$$

Individual S parameters are derived by measuring the incident and reflected waves with loads $Z_L = Z_0$ at the network's ports. In the case of the output line, where the load doesn't dissipate power, $V_2^+ = 0$, thus [18],

$$S_{11} = \frac{V_1^-}{V_1^+}\Big|_{V_2^+=0} \quad (3)$$

and the transmission parameter is [18]

$$S_{21} = \frac{V_2^-}{V_1^+}|_{V_2^+=0} \tag{4}$$

2.2. Cole – Cole and Debye Models

The dielectric constant values of different tissues are determined through the application of various models, such as the Debye model or the Cole–Cole model. In accordance with the Cole–Cole model, the estimation of dielectric constants can be achieved using equation 5

$$\hat{\varepsilon}(w) = \varepsilon_c'(\omega) - j\varepsilon_c''(\omega) = \varepsilon_\infty + \sum_n \frac{\Delta\varepsilon_n}{1+(j\omega\tau_n)^{(1-\alpha_n)}} + \frac{\sigma_i}{j\omega\epsilon_0} \tag{5}$$

where, ε_∞ is the high frequency permittivity, $\Delta\varepsilon_n$ is the magnitude of the dispersion, ω is the angular frequency, $\varepsilon_c'(\omega)$ is the frequency dependent dielectric constant, $\varepsilon_c''(\omega)$ is the frequency dependent dielectric loss, σ_i is the static ionic conductivity, n is the order of the Cole–Cole model, α_n is the parameter that allows for the broadening of the dispersion, and τ_n is the relaxation time constant [29]. In case of $\alpha_n = 0$ the equation reduces to Debye model and the term with the static conductance can be omitted for materials with low conductivity. Solutions of glucose/water can also be modelled with this model.

2.3. Vivaldi Antenna

Two vivaldi antennas were used for the study. Developed by Gibson in 1979, the Vivaldi antenna is used with very wide bandwidth characteristics and directional radiation patterns [30]. Vivaldi antenna offers advantages such as wide bandwidth, high directivity and bandwidth can be changed by changing some antenna parameters (shape, length, dielectric constant and dielectric thickness etc.). However, they are expensive due to the difficulties in the manufacturing phase. The structure of a vivaldi antenna is given in Figure 2 .

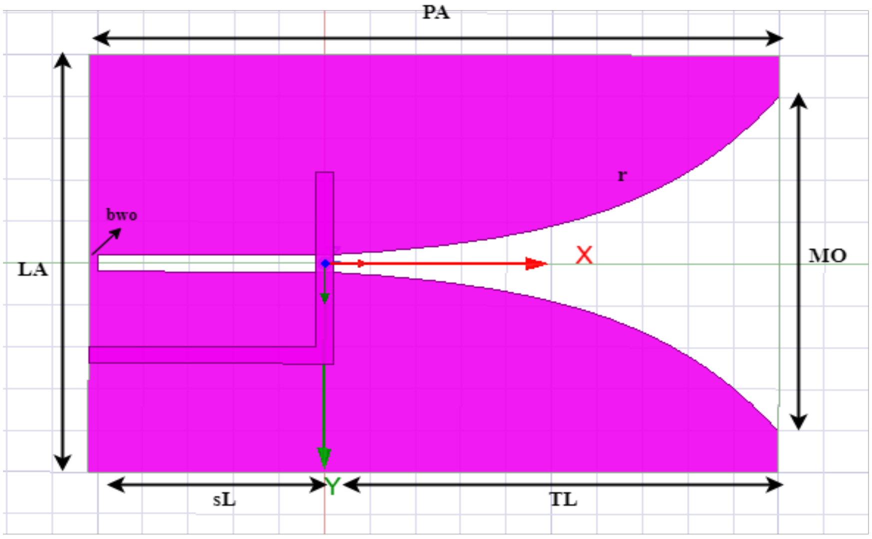

Figure 2. Vivaldi antenna

Dimension parameters of Vivaldi Antenna are antenna opening mouth (MO), slot-line length (sL), tapered length (TL), tapered rate (r), antenna width (LA), back-wall offset (bwo) and length (PA). The process of antenna design starts with establishing the fundamental antenna parameters on paper, laying the foundation for the upcoming steps. Once these parameters are determined, the next phase involves creating a virtual model of the antenna. This modeling is facilitated by an antenna simulation software, where the design is tested and analyzed based on the predetermined parameters. It's worth noting that the dimensions and size attributes of the antenna play a crucial role in determining its bandwidth and overall performance. Adjustments in these parameters can have a significant impact on how effectively the antenna operates within its intended frequency range [31].

The width (LA) and length (PA) of the antenna is determinated by equation (6,7)

$$PA \approx \frac{c}{f\sqrt{\epsilon_r}} \tag{6}$$

$$LA \approx \frac{1}{2} \times \frac{c}{f\sqrt{\epsilon_r}} \tag{7}$$

where LA is an antenna width, PA is a length, f is frequency, c is a speed of light and ϵ_r is a relative permittivity. In the design of Vivaldi antenna, the dimensions of tapered rate determine and tapered length calculation using equation (8). The slope level of the taper slot of Vivaldi antenna greatly affects the beam width, bandwidth and gain. In addition, the mouth opening value can be found using equation (9) [31].

$$u = \pm s \times exp^{(r\times t)} \tag{8}$$

$$\pm \frac{MO}{2} = \pm \frac{s}{2} \times exp^{(r\times TL)} \tag{9}$$

2.4. Experimental Setup and Measurements

The schematic diagram of experimental setup for monitoring the blood glucose level is shown in Figure 3. In the proposed system, the 5.5 GHz signal produced by the microwave wideband synthesizer is transmitted to the transmitting antenna via a coaxial cable. Here, electromagnetic waves interacting with the sample are collected in the receiving antenna and come to the power detector via the coaxial cable.

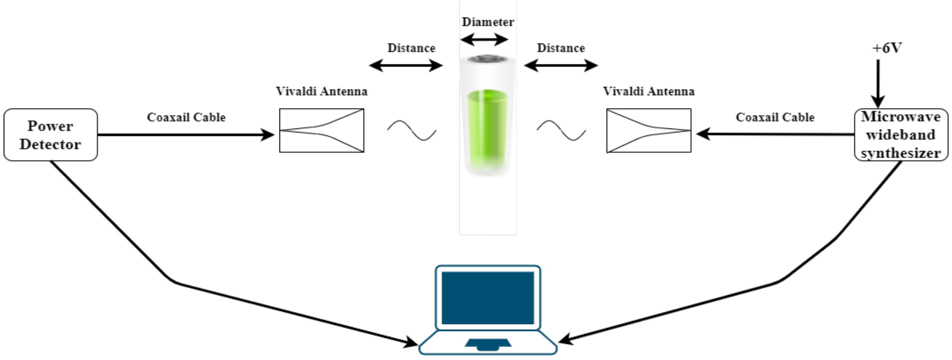

Figure 3. Schematic diagram of experimental setup

The primary benefit of the system we've implemented is its ability to bypass the vector network analyzer, a component frequently referenced in prior studies. This omission presents a significant cost-saving advantage. Furthermore, given the VNA's substantial size, it becomes impractical for long-term integration into commercial devices intended for everyday human use. Thus, by eliminating the VNA, our system paves the way for more streamlined and user-friendly applications In the study, the effect of the sample cup material (glass, plastic, etc.) on the measurement results was also investigated. The results of the measurements made using glass and plastic containers are presented in Table 1.

Table 1. Comparison of plastic and glass material

	Air	Plastic	Glass	Distilled Water	
				Plastic	Glass
-4 dBm	-25.6	-24.5	-28.8	-33.3	-33
-1 dBm	-19.8	-18.8	-22.3	-29.9	-31.2
+2 dBm	-16.5	-15.6	-18.9	-27	-28.9
+5 dBm	-14.1	-13.4	-17.6	-25.1	-27

When the measurement results made with air, empty plastic, empty glass, and plastic and glass tubes filled with pure water were examined, it was seen that the measurements made with plastic gave better results when compared to glass ones. In addition, the measurement results obtained for 50mg/dl, 125mg/dl, 250mg/dl, 500mg/dl and 1000mg/dl glucose solutions are given in Table 2. When these results were examined, it was seen that the measurement results made with the plastic cup gave better results than the glass.

Table 2. Measurements made in solutions of various glucose concentrations using a plastic cup

	50 mg/dL		125 mg/dL		250 mg/dL		500 mg/dL		1000 mg/dL	
	Plastic	Glass	Plastic	Glass	Plastic	Glass	Plastic	Glass	Plastic	Glass
-4 dBm	-33.5	-34.9	-33.7	-34.5	-33.8	-33	-33.9	-32.5	-33.9	-34
-1 dBm	-29.9	-31.1	-29.7	-31.3	-29.1	-31.2	-29.4	-31.7	-29.8	-31.5
+2 dBm	-26.8	-28.6	-26.5	-29	-25.6	-28.5	-25.9	-29.5	-26.8	-29
+5 dBm	-24.2	-27	-24.1	-27.6	-24.3	-27.1	-24.5	-27	-24.8	-27.1

With the plastic material giving better results than glass, the effects of the diameters of the plastic sample cups on the measurement results were investigated. Sample cups with diameters of 20.5 mm and 22.8 mm were used and these cups are shown in Figure 4.

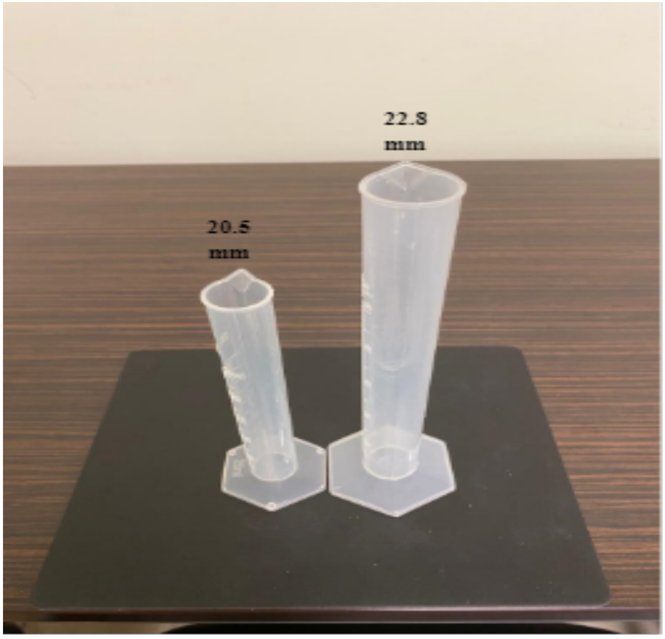

Figure 4. Plastic sample cups of 20.5 mm and 22.8 mm

The measurement results with 20.5 mm and 22.8 mm plastic cups are given in Table 3. When Table 3 is examined, it is seen that there is an improvement in the data obtained from the power detector with the reduction of the measuring cup diameter.

Table 3. Effect of measuring cups with diameters of 20.5 mm and 22.8 mm on measurement results

	50 mg/dL		125 mg/dL		250 mg/dL		500 mg/dL		1000 mg/dL	
	22.8 mm	20.5 mm	22.8 mm	20.5 mm	22.8 mm	20.5 mm	22.8 mm	20.5 mm	22.8 mm	20.5 mm
-4 dBm	-33.5	-33.4	-33.7	-33.2	-33.8	-33.1	-33.9	-33.4	-33.9	-33.7
-1 dBm	-29.9	-29.1	-29.7	-28.5	-29.1	-28.7	-29.4	-28.5	-29.8	-29.1
+2 dBm	-26.8	-25.2	-26.5	-25.9	-25.6	-25.1	-25.9	-25.7	-26.8	-26.2
+5 dBm	-24.2	-23.7	-24.1	-23.8	-24.3	-23.7	-24.5	-23.6	-24.8	-23.9

In the research thus far, the impact of both the measuring cup's material (plastic versus glass) and its diameter (20.5 mm and 22.8 mm) on the results is explored. From our observations, plastic cups outperform their glass counterparts, and cups with a smaller diameter yield better outcomes. In the next part of the research, the effect of the distance of the receiving and transmitting antennas to the measuring cup on the measurement result is examined.

The objective of antenna simulation is to evaluate and determine whether the designed antenna model aligns with the predefined specifications. In the context of this research, the antennas in consideration are commercial products sourced from China. Unfortunately, these products lack detailed datasheets and a Gerber file. To overcome this limitation and gain insights into the approximate characteristics of the antenna, a modeling process is proposed. We employed the

ANSYS-HFSS software, a leading tool in the electromagnetic simulation domain, to recreate and analyze the antenna's behavior and performance. The size parameters of the modeled antenna and the design of the antenna are presented in Figure 5.

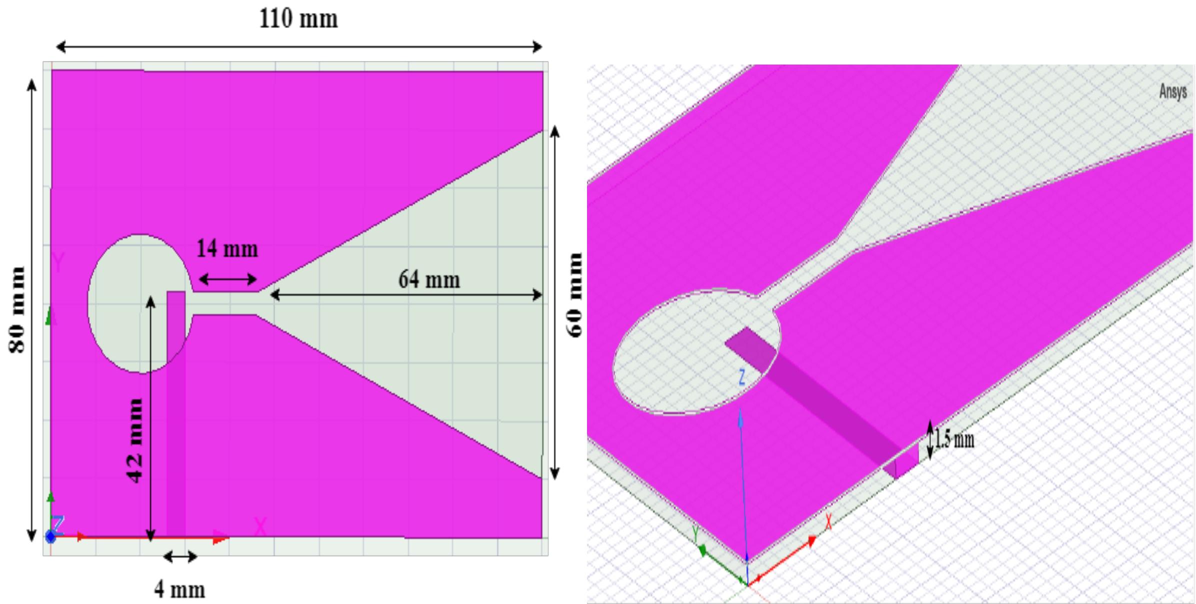

Figure 5. Vivaldi antenna view from the upper z-axis and vivaldi antenna thickness

In order to examine the distance of the antennas to the measuring cup, the setup in Figure 6 was set up. Measurements were taken as 0.5 cm, 1.5 cm, 2.5 cm, 3.5 cm and 4.5 cm distances from the antennas to the measuring cup.

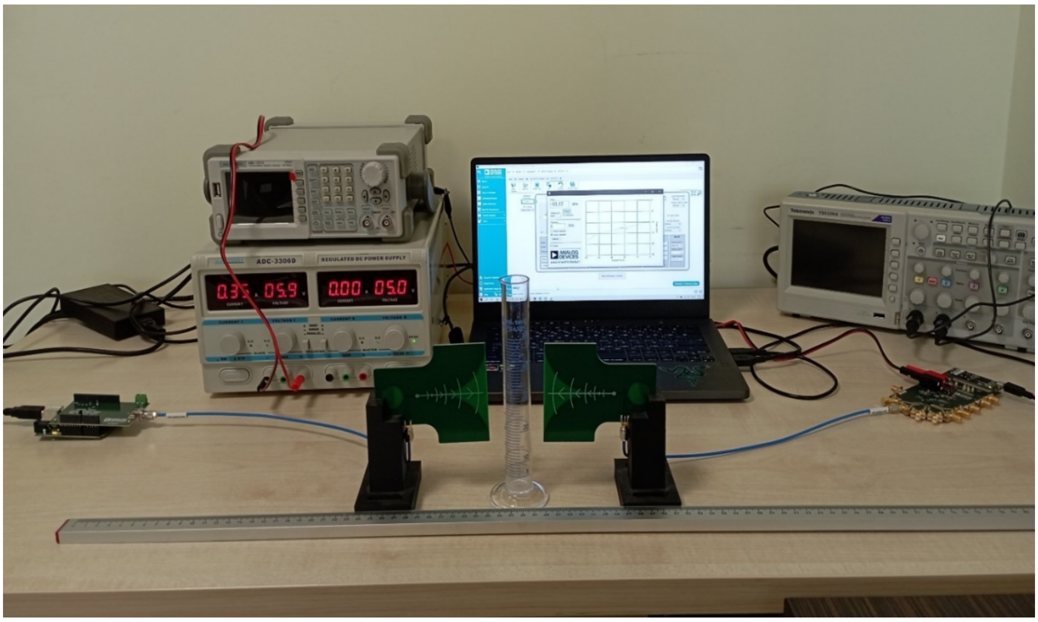

Figure 6. Experimental setup

With the installation in Figure 5, both the distance of the antennas to the test tube and the effect of the diameters were examined together. Plastic test tubes with diameters of 22.8 mm and 20.5 mm were used for the measurements. The glucose solution concentrations used during the experiment are 50 mg/dL, 125 mg/dL, 250 mg/dL, 500 mg/dL and 1000 mg/dL.

Table 4. Effect of the distance between the antennas and the test tube on the measurement results.

Distance between sample and antenna: 0.5 cm										
	50 mg/dL		125 mg/dL		250 mg/dL		500 mg/dL		1000 mg/dL	
	22.8 mm	20.5 mm	22.8 mm	20.5 mm	22.8 mm	20.5 mm	22.8 mm	20.5 mm	22.8 mm	20.5 mm
-4 dBm	-34	-32.5	-34.1	-33.2	-34.3	-33.5	-34.5	-34	-35	-32
-1 dBm	-32.5	-28.8	-33	-27.8	-32.9	-30.5	-33.5	-30.8	-33	-30.9
+2 dBm	-31.6	-26.3	-31.5	-25.9	-31.4	-27.1	-31.4	-26.8	-31.3	-28.1
+5 dBm	-30.2	-24.1	-29.5	-23.4	-30.1	-25.2	-27.9	-25.6	-30.1	-25.8
Distance between sample and antenna: 1.5 cm										
	50 mg/dL		125 mg/dL		250 mg/dL		500 mg/dL		1000 mg/dL	
	22.8 mm	20.5 mm	22.8 mm	20.5 mm	22.8 mm	20.5 mm	22.8 mm	20.5 mm	22.8 mm	20.5 mm
-4 dBm	-33.6	-32.7	-33.4	-32.5	-34.1	-33.2	-33.1	-32.8	-32.5	-32.4
-1 dBm	-28.7	-28.4	-29.8	-27.7	-30.5	-28.1	-28.4	-28.2	-27.8	-27.4
+2 dBm	-25.6	-25.1	-27.7	-24.6	-28.2	-24.3	-27.7	-24.7	-25.4	-25.1
+5 dBm	-24.1	-24.1	-25.2	-22.8	-25.7	-22.3	-24	-22.3	-23.3	-22.2
Distance between sample and antenna: 2.5 cm										
	50 mg/dL		125 mg/dL		250 mg/dL		500 mg/dL		1000 mg/dL	
	22.8 mm	20.5 mm	22.8 mm	20.5 mm	22.8 mm	20.5 mm	22.8 mm	20.5 mm	22.8 mm	20.5 mm
-4 dBm	-33.5	-33.4	-33.7	-33.2	-33.8	-33.1	-33.9	-33.4	-33.9	-33.7
-1 dBm	-29.9	-29.1	-29.7	-28.5	-29.1	-28.7	-29.4	-28.5	-29.8	-29.1
+2 dBm	-26.8	-25.2	-26.5	-25.9	-25.6	-25.1	-25.9	-25.7	-26.8	-26.2
+5 dBm	-24.2	-23.7	-24.1	-23.8	-24.3	-23.7	-24.5	-23.6	-24.8	-23.9
Distance between sample and antenna: 3.5 cm										
	50 mg/dL		125 mg/dL		250 mg/dL		500 mg/dL		1000 mg/dL	
	22.8 mm	20.5 mm	22.8 mm	20.5 mm	22.8 mm	20.5 mm	22.8 mm	20.5 mm	22.8 mm	20.5 mm
-4 dBm	-36.6	-35.1	-36.4	-34.8	-37	-34.2	-35.3	-34.1	-34.8	-33.9
-1 dBm	-32.7	-30.1	-33.1	-29.8	-32.8	-29.4	-32.6	-28.9	-31.6	-29.5
+2 dBm	-29.3	-26.5	-30.1	-26.8	-30.5	-26.5	-30.3	-26.2	-30.7	-25.6
+5 dBm	-28.8	-24.9	-28.1	-23.8	-27.8	-24.7	-27.6	-24	-28.8	-23.9
Distance between sample and antenna: 4.5 cm										
	50 mg/dL		125 mg/dL		250 mg/dL		500 mg/dL		1000 mg/dL	
	22.8 mm	20.5 mm	22.8 mm	20.5 mm	22.8 mm	20.5 mm	22.8 mm	20.5 mm	22.8 mm	20.5 mm
-4 dBm	-35.1	-33.1	-35.7	-32.9	-36.2	-32.5	-36.8	-32.8	-36.4	-32.1
-1 dBm	-32.3	-28.6	-31.5	-28.2	-32.3	-28.4	-32.9	-28.1	-32.7	-28.4
+2 dBm	-30.1	-25.6	-30.4	-25.4	-29.1	-24.8	-30	-24.7	-29.8	-25
+5 dBm	-29.2	-23.5	-28.5	-23	-28.5	-23	-28.8	-23.1	-28.6	-22.6

The 5.5 GHz signal generated by the microwave wideband synthesizer is directed to the sample by the transmitting antenna. Signals passing through the sample are collected by the receiving antenna on the opposite side and sent to the power detector. When the data obtained from the power detector in Table 4 are examined, signal distortions occurred when the antennas and the sample were too close ($< 1.5\ cm$) or too far ($> 4.5\ cm$) away. In addition, the data obtained at 1.5 cm, 2.5 cm and 3.5 cm were found to be consistent within themselves. As it is consistent with the Table 3, 20.5 mm results are superior to 22.8 mm ones.

3. Conclusion

As a result, in this study, it is aimed to determine the optimum test conditions for glucose level determination with a non-invasive method at 5.5 GHz. In this context, firstly, the test tube material was examined and it was seen that better results were obtained in plastic material than in glass material. The reason for this is that the signals coming to the glass material are more scattered than the plastic material. Then, the effects of the diameters of the plastic test tubes on the measurement results were examined. By reducing the diameter of the measuring cup, better data were obtained in the power detector. In the last study, the effect of the distance of the antennas from the sample cup on the measurement results was investigated. When these results were examined, it was observed that the signal was scattered when the antennas were adjacent to the sample cup and the distance increased. As a future work, it is aimed to obtain healthier and more reliable data by taking signals as continuous data and applying signal processing algorithms. In addition, antenna structures will be compared by taking measurements at different frequencies with various antenna types.

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