J. Electrical Systems 20-3 (2024):6514-6524

[1]Asha Ghodake
[2]Hanamant Sale

Glucose Level Monitoring Using Large Bandwidth Wearable Microstrip Antenna

Abstract: - Monitoring blood sugar levels are important for several reasons. To effectively manage diabetes, glucose level monitoring is essential for preventing complications, improving quality of life, and advancing current medical research. This study investigates the idea of using microstrip antennas, which are lightweight and tiny, to track blood glucose levels. The dielectric characteristics of the blood alter in response to changes in blood glucose levels, which has an impact on the microstrip antenna's resonant frequency that was applied to the body. It is possible to determine real-time glucose levels increase or decrease by examining these frequency shifts. The variation in glucose levels is directly proportional to the antenna operating frequency. There are two antennas used: one with a bandwidth of 1.5 GHz and another with a bandwidth of 200 MHz made of jeans. Large bandwidth antennas offer the greatest frequency shift in response to variations in blood glucose levels. Two on-body sites were selected for observing glucose levels, one is a finger and the other is the arm. High-Frequency Structure Simulator (HFSS) software was used to perform this study. The blood layer dielectric constant falls and the antenna's output frequency rises with rising glucose levels. Specific absorption rate (SAR) analysis is also carried out to check the effect of RF radiation. The study highlights the potential of microstrip antennas in improving glucose monitoring systems while reviewing recent developments and discussing wearable technologies and portable medical devices.

Keywords: Monitoring, Blood, Microstrip, Wearable, Antenna.

I. INTRODUCTION

Monitoring blood sugar levels is crucial for several reasons, especially for those who have diabetes or are at risk of developing blood sugar problems. Frequent glucose monitoring aids in blood sugar management for diabetics. To keep blood glucose levels within a desired range and avoid issues, it enables people to modify their diet, level of exercise, and use of medicine. Regular monitoring aids in the prevention of long-term complications such as renal disease, nerve damage, cardiovascular disease, and eye problems, as well as short-term concerns such as hypoglycemia (high blood sugar) and hyperglycemia (low blood sugar). Data from monitoring lets medical professionals customize treatment regimens, such as insulin dosages or other prescriptions, based on each patient's unique glucose requirements and patterns [1].

Frequent monitoring can assist people and healthcare professionals in understanding how things like meals, stress, and exercise affect blood sugar by revealing patterns and trends in blood glucose levels. People can make educated decisions about their food, level of physical activity, and other lifestyle factors that affect blood sugar control by monitoring their glucose levels. Monitoring enables quick action to address problems such as hypoglycemia or hyperglycemia in cases of unexpected glucose level fluctuations, lowering the risk of severe symptoms or emergencies [2]. Good glucose monitoring lowers the chance of complications from diabetes and improves daily well-being, all of which lead to improved overall health management. Glucose monitoring can be used by people without diabetes to determine their risk of getting diabetes as well as to understand how certain diets, activities, and medical conditions affect blood sugar levels [3].

Monitoring blood sugar levels is essential for controlling diabetes and maintaining general health. Monitoring glucose levels can be done in a few different ways. A tiny blood sample is needed for blood glucose meters, and this is often taken by pricking your finger. To get a reading, place the drop of blood on a test strip and insert it into the meter. It's a standard procedure for everyday observation. Your average blood glucose levels over the previous two to three months are measured by an A1C test [4]. It is used to evaluate long-term glucose management and is usually performed in the office of a healthcare professional. You can use urine test strips to determine whether your

---

[1] *Corresponding author: Department of Electronics and Telecommunication Engineering, Bharati Vidyapeeth College of Engineering, Navi Mumbai, Maharashtra, India

[2] Department of Information Technology Engineering, Bharati Vidyapeeth College of Engineering, Navi Mumbai, Maharashtra, India

urine contains glucose. This less accurate strategy is typically employed in situations where alternative options are unavailable.

Continuous glucose monitors (CGMs) are wearable gadgets that track a person's blood sugar levels all day long. To measure the amount of glucose in the interstitial fluid, they implant a tiny sensor under the skin, which then transmits the information to a receiver or smartphone app. CGMs can notify you of high or low glucose levels and offer readings more often. Glucose flash monitors are these devices that use a skin-worn sensor, just like CGMs [5]. To obtain a glucose reading, you use a reader to scan the sensor rather than constantly monitoring it. Although it doesn't enable constant real-time monitoring, it does offer statistics on glucose patterns.

Numerous uses for microstrip antennas have been investigated, including monitoring systems and medical diagnostics. These antennas are usually utilized in non-invasive glucose level monitoring techniques. A review of the literature that highlights important studies on the use of microstrip antennas for glucose level monitoring is provided below. The use of microwave sensors, such as microstrip antennas, for non-invasive glucose monitoring is investigated in this review paper. It covers several design factors that impact these sensors' performance, such as material selection and frequency selection. The advantages of microstrip antennas—their small size and simplicity of integration with wearable devices—are highlighted in the article [6].

The design of a microstrip patch antenna specifically intended for non-invasive glucose testing is presented in this study [7] [8]. The design factors of the antenna, including its size, shape, and substrate material, are discussed by the authors along with how they affect the performance of the sensor. Additionally, they offer experimental findings demonstrating the antenna's ability to detect variations in glucose content.

This study [9] investigates the usage of microstrip antennas with microwave and millimeter-wave frequencies for non-invasive glucose monitoring. The theoretical underpinnings of how glucose impacts microwave signal propagation and antenna design for best-in-class performance in glucose sensing systems are covered in this work.

This research [10] presents a non-invasive glucose monitoring device based on microstrip antennas. The system's architecture, including the antenna and signal processing unit, is described, and experimental results showing how well the device measures glucose levels non-invasively are presented.

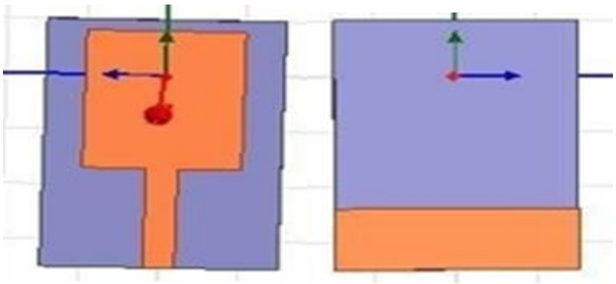
The design and analysis of a microstrip antenna utilized in a wearable device for non-invasive glucose testing are examined in this study [11]. It goes through the sensitivity and accuracy of the antenna as well as how it works with the other parts of the wearable gadget. Microstrip antennas' small size, ease of integration, and capacity to function at microwave frequencies have made them promise for use in non-invasive glucose monitoring. The examined papers show continuous progress in the development of these antennas' design and use in medical diagnostics. Future studies might concentrate on boosting integration with wearable technology, cutting down on power use, and increasing accuracy.

One popular kind of wearable antenna is a microstrip antenna composed of textiles or cloth. Wearable systems require antenna-embedded textile structures to enable on-body wireless transmission via clothing [12]. Body-centric devices that patients wear can electronically alert healthcare professionals about a patient's health condition, enabling them to provide more effective patient care and take urgent action when needed. Information transmission is made efficient by wearable antennas, sometimes known as integrated antennas [13] [14].

The textile patch antenna is one of several types of antennas that are frequently utilized for wearable applications. Because of their planar architecture, flexibility, low weight, and aesthetically pleasing appearance, they are suitable for wearable products. Between the bottom and top layers of a microstrip patch antenna is a non-conducting substance composed of conducting material [15][16]. In this paper, two microstrip antennas are designed using jeans substrates to monitor glucose levels. These antennas act as wearable antennas. By finger and arm tissue glucose monitoring was done

II. ANTENNA DESIGN

Two jeans antennas were designed for glucose level monitoring; one with a large bandwidth (1.5 GHz), and the other with a smaller bandwidth than the first (200 MHz). The substrate properties are $\varepsilon r = 1.6$ and $\tan \delta = 0.01$ [17]. The designed antenna is shown in Figure 1.



(a) (b)

Fig. 1 Projected antenna (a) Face (b) Reverse Side

In antenna design, a fractional ground length is used. Fig. 2 depicts the antenna operating frequency of 2.4 GHz and obtained reflection coefficient is -22.41 dB. The bandwidth obtained for this antenna is 1.5 GHz displayed in Figure 2. Partial ground plane was used for this antenna.

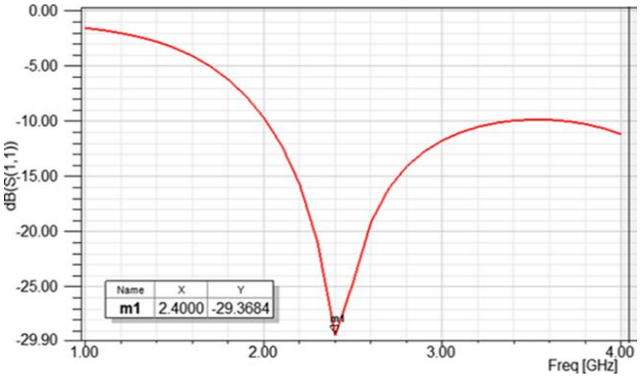
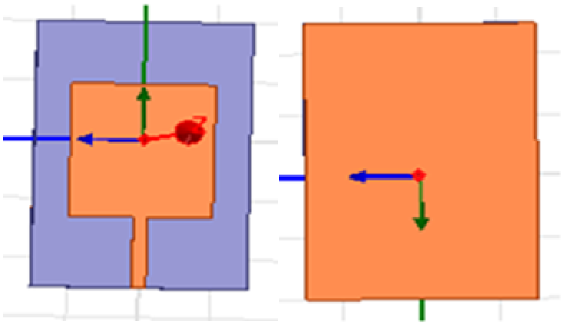


Fig. 2 S11 plot

The second designed antenna is shown in Figure 3. This antenna is also made of jeans substrate. For patch and ground plane copper material was used. Complete ground plane was used for this antenna.



(a) (b)

Fig. 3 Made-up antenna (a) Face (b) Flipside

The bandwidth obtained using this antenna was 200 MHz shown in Figure 4.

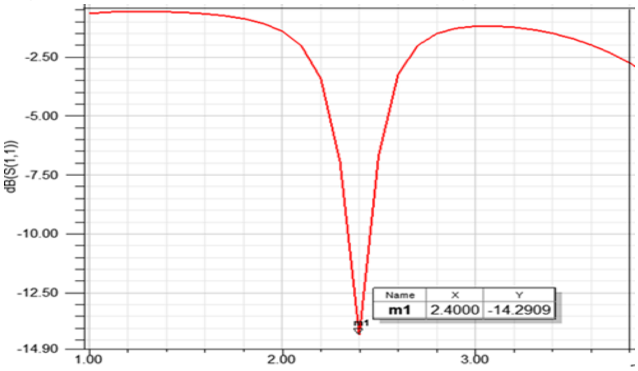


Fig. 4 Output frequency of Antenna

Both the antennas were operated in the ISM band between 2.4 GHz to 2.5 GHz.

III. Specific Absorption Rate (SAR) Analysis

People wear these textile antennas, so it's important to investigate how antenna radiation affects the human body. The body's electromagnetic energy is computed in terms of surface area ratio (SAR). Impedance mismatching causes some transmitted power to be reflected when the antenna is near a body [18].

Analysis of the specific absorption rate (SAR) is essential for wearable antenna. This investigation determines how wearable antennas affect the body with electromagnetic radiation. Standard values for the SAR limit based on average body mass are provided. Human health is unaffected by electromagnetic radiation when SAR is less than 1.6 W/kg [19] [20]. Figure 5 depicts the obtained SAR value as 0.667 W/kg.

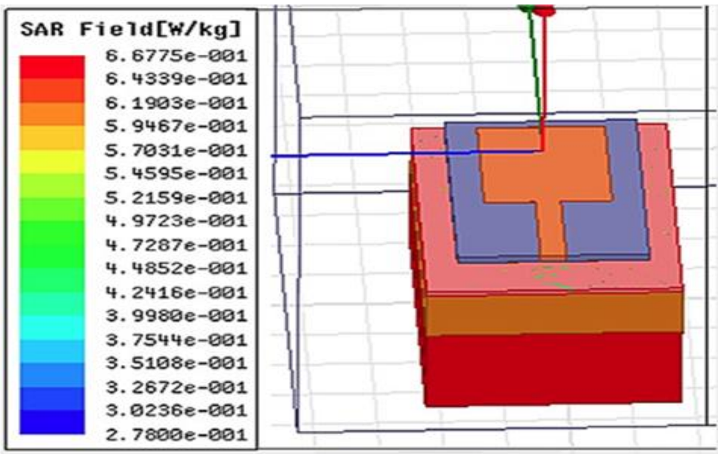


Fig. 5 SAR output using 1.5 GHz bandwidth antenna.

Similarly, an antenna having 200 MHz bandwidth was placed on the tissue for this analysis, and results were observed. The modelled tissue is shown in Figure 6.

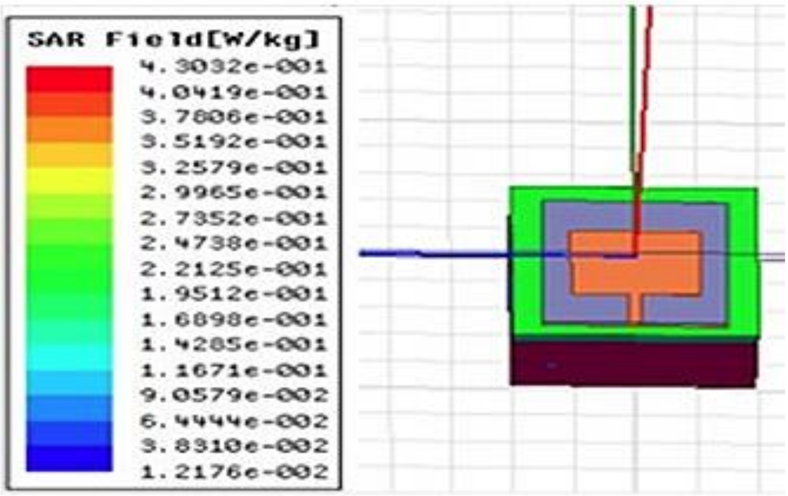


Fig. 6 SAR output using 200 MHz bandwidth antenna.

The observed SAR was 0.430 W/kg. Every measured SAR value was below the IEEE-specified SAR limit for 1 g of tissue. For SAR analysis, the antenna needs to receive at least 1 mW of power. Specific absorption rate analysis was carried out using HFSS software.

IV. Methodology

The workflow diagram of glucose level monitoring is shown in Figure 7. The idea behind glucose level monitoring is that variations in blood glucose cause the blood's dielectric characteristics to change, which in turn modifies the output frequency of an antenna worn on the body [21]. Two areas for measurements are chosen for this supervision: one finger and one human arm. The operating frequency of the antenna rises in proportion to the glucose level.

Thus, one characteristic that is used for blood glucose level monitoring is the output frequency. Finger and arm tissue were simulated using HFSS and by placing the antenna on this tissue, output frequency shift was observed. So, glucose level monitoring is according to output frequency shift.

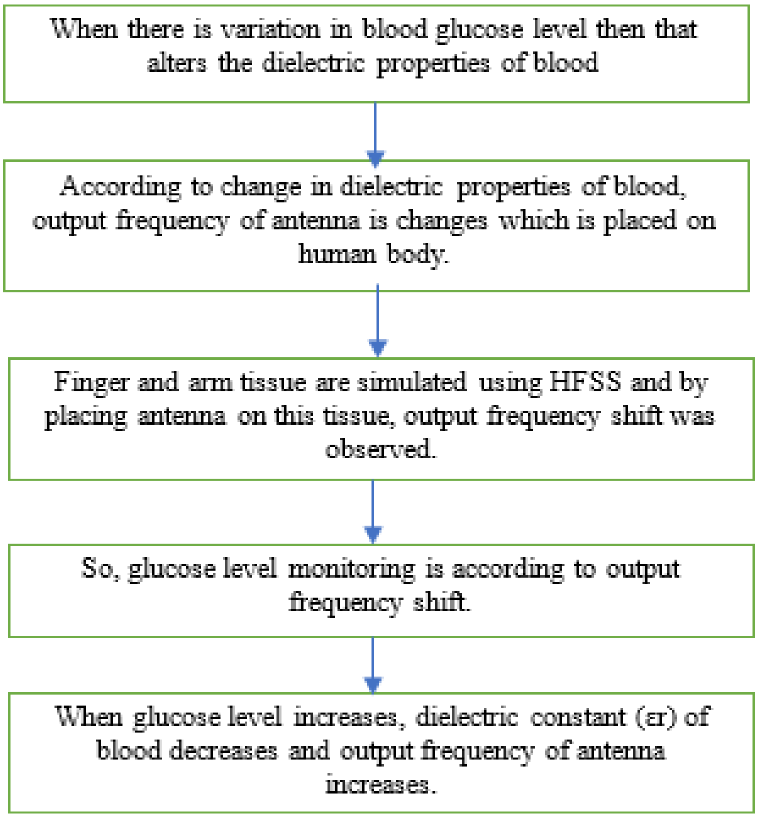


Fig. 7 Workflow diagram of glucose level monitoring

V. RESULTS

A. *Glucose level monitoring using 1.5 GHz bandwidth jeans antenna.*

HFSS software was used to model the tissues of the finger and arm to monitor glucose levels. Operational frequency fluctuation in the output was found by applying finger and arm tissues on the antenna patch. The software's material setting was used to change the dielectric constant of the blood layers at each stage of the simulation.

A.1 Simulation results using finger.

As seen in Table 1, the first example involved designing finger tissue in HFSS software by utilizing several layers such as skin, bone, blood, and muscle. At 2.4 GHz, the blood layer parameters are $\sigma = 2.5$ and $\mathcal{E}r = 58$ [22]. After that, finger tissue was placed on the antenna patch, and the material setting in HFSS was used to alter the blood layer's dielectric constant at each stage of the simulation, and the output frequency of the antenna was observed.

Table 1 Finger tissue layers with its dielectric properties

Tissue Layers	**Permittivity (εr)**	**Conductivity (σ) S/m**	**Loss Tangent (tan δ)**	**Layer Height (mm)**
Skin	31.29	8.0138	0.2835	1
Fat	4.60	0.5852	0.1938	0.5
Blood	58	2.5	0.242	5
Bone	20	1.705	0.2419	4

The simulated diagram in which finger tissue was placed on the antenna patch is shown in Figure 8.

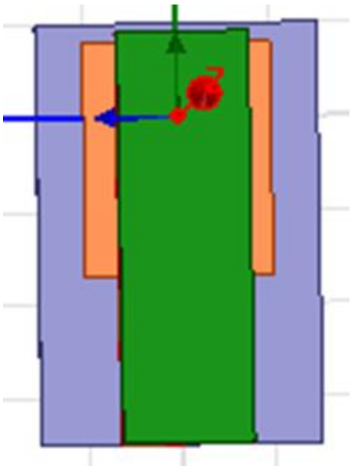


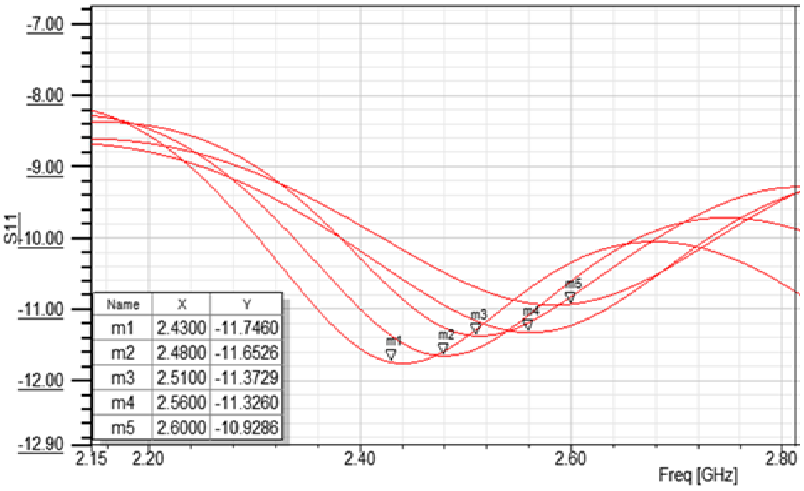
Fig. 8 Finger tissue placed on antenna patch.

The simulation results are shown in Table 2 after the blood layer's parameters are changed in each step. As the blood dielectric constant (Ɛr) decreases, the antenna's operating frequency increases.

Table 2 Blood glucose level vs. resonant frequency (simulation results using a finger)

Ɛr	**σ**	**f (GHz)**	**S11 (dB)**
58	2.5	2.4300	-11.74
53.9	2.5	2.4800	-11.65
49.1	2.5	2.5100	-11.37
43.8	2.5	2.5600	-11.32
40	2.5	2.6000	-10.92

When the dielectric constant was 58, the determined frequency was 2.4300 GHz with an S11 of -11.74 dB; similarly, when the dielectric constant was 40, the frequency was 2.600 GHz with a loss of -10.92 dB. Consequently, the output frequency of the antenna increases as the blood's dielectric constant lowers. Figure 9 displays the output of the simulation.



Name	X	Y
m1	2.4300	-11.7460
m2	2.4800	-11.6526
m3	2.5100	-11.3729
m4	2.5600	-11.3260
m5	2.6000	-10.9286

Fig. 9 Variation in output frequency w.r.t Ɛr using a finger.

A.2 Simulation results using arm.

As seen in Figure 10, in the second scenario, arm tissue was simulated, and an antenna was positioned on the arm tissue.

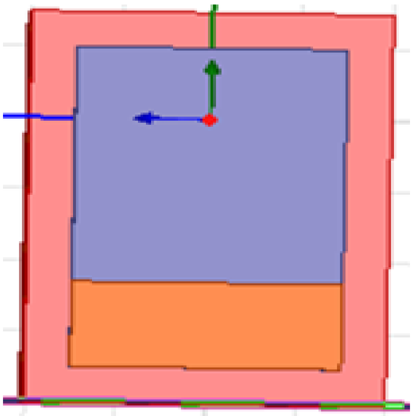


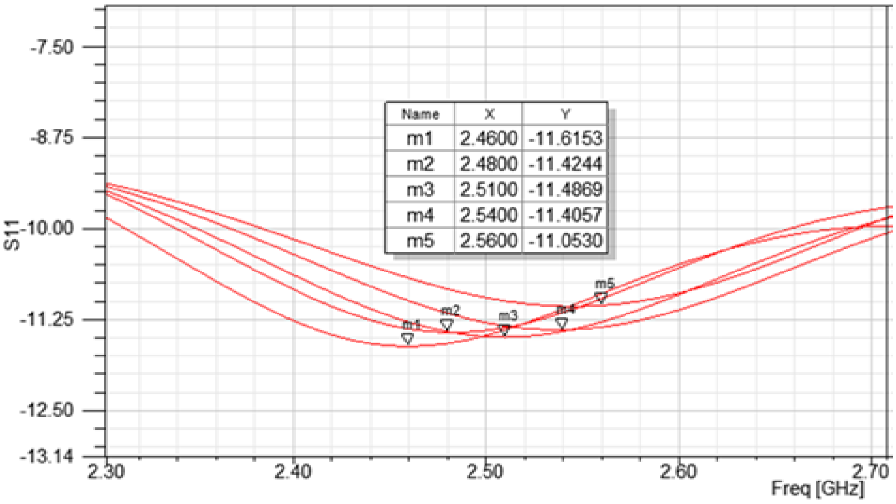
Fig. 10 Antenna placed on arm tissue.

Every step of the way, the antenna's working frequency was monitored per changes in the blood-layer parameters. Table 3 lists the layers that were utilized in the arm tissue along with their respective characteristics.

Table 3 Finger tissue layers with its dielectric properties

Tissue Layers	Permittivity (εr)	Conductivity (σ) S/m	Loss Tangent (tan δ)	Layer Height (mm)
Skin	31.29	8.0138	0.2835	2
Fat	4.60	0.5852	0.1938	10
Blood	58	2.11	0.242	5
Muscle	52.79	1.705	0.2419	20

Figure 11 shows the outputs that were obtained. This figure illustrates how the antenna's frequency moves from 2.4600 GHz to 2.5600 GHz as the dielectric constant value falls.



Name	X	Y
m1	2.4600	-11.6153
m2	2.4800	-11.4244
m3	2.5100	-11.4869
m4	2.5400	-11.4057
m5	2.5600	-11.0530

Fig. 11 Variation in output frequency w.r.t Ɛr using arm.

A summary of Figure11 is included in Table 4. Blood's dielectric constant drops from 58 to 40, at which point the antenna's output frequency rises. The obtained frequency was 2.4600 GHz at a dielectric constant of 58, while the received frequency was 2.5600 GHz at a dielectric constant of 40. However, S11 did not experience a linear rise or fall.

Table 4 Blood glucose level vs. resonant frequency (simulation results using a finger)

Ɛr	σ	f (GHz)	S11 (dB)
58	2.5	2.4600	-11.61
53.9	2.5	2.4800	-11.42
49.1	2.5	2.5100	-11.48

43.8	2.5	2.5400	-11.40
40	2.5	2.5600	-11.05

Based on the outputs that were collected, it was determined that the antenna's resonant frequency increases as the blood's dielectric constant lowers. There exists an inverse proportionality between the blood's dielectric constant and glucose level. Thus, the blood's dielectric constant falls and the antenna's output frequency rises as blood glucose levels rise. Thus, there was a rise in the antenna's output frequency as the glucose level rose.

When a finger was used as the measuring point instead of an arm, the greatest frequency change was seen. For the finger, the total frequency shift was 0.17 GHz (6.99 %) when Ɛr = 58, then f = 2.4300 GHz, and when Ɛr = 40, then f = 2.6000 GHz. Similarly, with the arm, the overall frequency shift was 0.1 GHz (4.06%) when Ɛr = 58, then f = 2.4600 GHz, and when Ɛr = 40, then f = 2.5600 GHz. As a result, finger monitoring yielded better findings than arm monitoring when it came to frequency shift. Furthermore, a finger was used to bring about a linear change in S11.

B. Glucose level monitoring using 200 MHz bandwidth jeans antenna.

Two locations for measurements are chosen: the finger and the arm, the same as with the prior antenna.

B.1 Glucose level monitoring using a finger.

In this instance, the finger tissue was placed on the antenna patch to monitor the glucose level shown in Figure 12. Using the material settings in the HFSS software, the blood layer's characteristics were changed at each stage of the measurement.

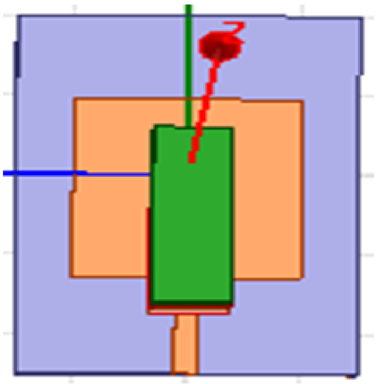
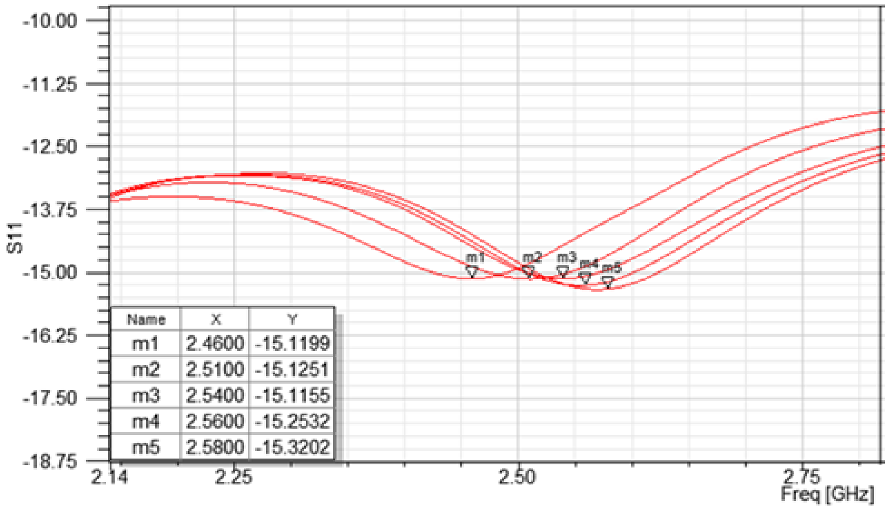


Fig. 12 Simulated finger tissue is placed on an antenna patch.

So, antenna output frequency variation occurs from 2.4600 GHz to 2.5800 GHz according to different dielectric constants of the blood layer shown in Figure 13.



Name	X	Y
m1	2.4600	-15.1199
m2	2.5100	-15.1251
m3	2.5400	-15.1155
m4	2.5600	-15.2532
m5	2.5800	-15.3202

Fig. 13 Output frequency variation using simulated finger tissue.

Table 5 demonstrates that when the dielectric constant drops from 58 to 40, the antenna's working frequency rises. The antenna's output frequency was 2.4600 GHz at a dielectric constant of 58 and 2.5800 GHz at a dielectric constant of 40. Between high and low glucose levels, there was a 0.12 GHz (4.87%) frequency change.

Table 5 Frequency variation according to Ɛr using a simulated finger.

Ɛr	**σ**	**f (GHz)**	**S11 (dB)**
58	2.5	2.4600	-15.11
53.9	2.5	2.5100	-15.12
49.1	2.5	2.5400	-15.11
43.8	2.5	2.5600	-15.25
40	2.5	2.5800	-15.32

B.2 Glucose level monitoring using the arm.

The antenna was positioned on the arm tissue in this instance (Figure 14), the material setting was used to adjust the blood dielectric constant from 58 to 40, and an output frequency shift was seen (Figure 15).

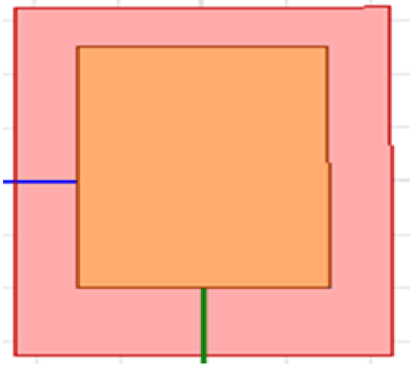
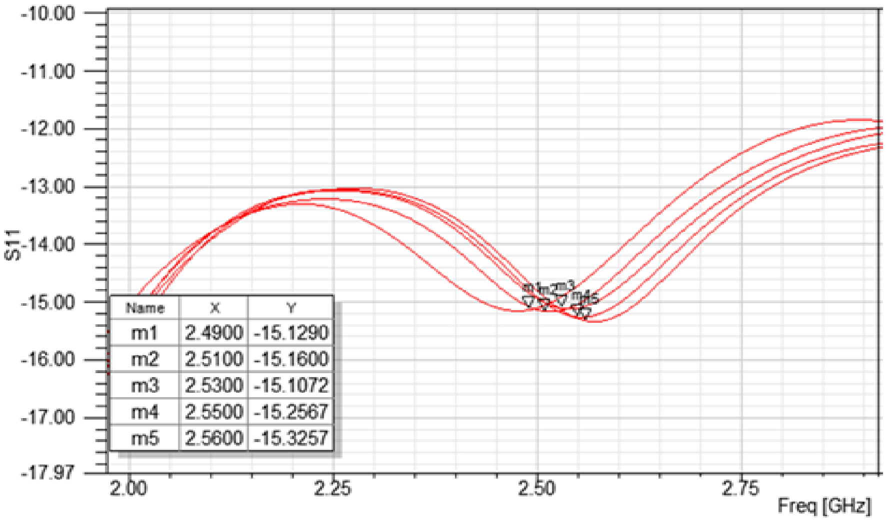


Figure 14. Simulated antenna placed on arm tissue.

Antenna output frequency varies between 2.4900 GHz and 2.5600 GHz under variations in the blood layer's dielectric constant.



Name	X	Y
m1	2.4900	-15.1290
m2	2.5100	-15.1600
m3	2.5300	-15.1072
m4	2.5500	-15.2567
m5	2.5600	-15.3257

Fig. 15 Output frequency variation using arm tissue.

Table 6 shows that the resonating frequency of the antenna increases when the dielectric constant decreases from 58 to 40. The antenna's output frequency was 2.4900 GHz at a dielectric constant of 58 and 2.5600 GHz at a dielectric constant of 40. Between high and low glucose levels, there was a 0.07 GHz (2.81%) frequency change.

Table 6 Frequency variation according to Ɛr using a simulated finger.

Ɛr	**σ**	**f (GHz)**	**S11 (dB)**
58	2.5	2.4900	-15.12

53.9	2.5	2.5100	-15.16
49.1	2.5	2.5300	-15.10
43.8	2.5	2.5500	-15.25
40	2.5	2.5600	-15.32

By placing the full-ground plane antenna on the arm or by putting a finger on the antenna patch, glucose levels were observed according to changes in antennas output frequency. Using output frequency shift monitoring, the blood glucose level was tracked. The finger 0.12 GHz (4.87%) yielded a greater maximum frequency shift than the arm 0.07 GHz (2.81%), and the frequency shift was smaller than that of the 1.5 GHz bandwidth antenna.

Finally, Table 7 includes the simulated results of the 1.5 GHz bandwidth antenna and the 200 MHz bandwidth antenna for the measurement of glucose levels. It demonstrates that the finger, not the arm, was used to achieve the highest frequency shift. Also, a high bandwidth antenna produced good results and the largest frequency shift.

Table 7 Detailed glucose level monitoring results in terms of frequency shift

	Antenna Type			
	Antenna of 1.5 GHz bandwidth		**Antenna of 200 MHz bandwidth**	
	Simulation Results			
Dielectric constant/Measurement site	**Output Frequency Using Simulation**		**Output Frequency Using Simulation**	
	Finger	**Arm**	**Finger**	**Arm**
58	2.43 GHz	2.46 GHz	2.46 GHz	2.49 GHz
40	2.60 GHz	2.56 GHz	2.58 GHz	2.56 GHz
Output Frequency Shift	0.17 GHz (6.99 %)	0.1 GHz (4.06%)	0.12 GHz (4.87%)	0.07 GHz (2.81%)

VI. CONCLUSION

The glucose level was monitored using both jeans antennae. The first Jeans antenna with a 1.5 GHz bandwidth. The second antenna for jeans has a 200 MHz bandwidth. The finger and the arm were chosen as the two measurement locations for the glucose level monitoring. By mimicking the tissue of the fingers and arms and adjusting the blood layer dielectric constant in HFSS, simulation results were obtained. SAR analysis was also carried out and the obtained SAR value is under the limit provided by IEEE standards. So designed antenna is useful for wearable applications. This idea was applied to the monitoring of blood glucose levels, as the blood layer's dielectric constant lowers, the antenna's output frequency rises. According to the results of the simulation, the greatest frequency fluctuation was achieved with an antenna with a broad bandwidth and a finger rather than an arm. With the largest frequency shift, glucose level monitoring with jeans antennas with huge bandwidth was feasible. This method has the advantages of being less intrusive, cost-effective, and requiring continuous monitoring.

REFERENCES

[1] M. A. Basha, R. H. Zaghloul, M. Alkordi, “Minimally invasive body-fluids analyzer for continuous glucose monitoring,” USNC-URSI Radio Science Meeting (Joint with AP-S Symposium), June 2014.

[2] Morrish, N. J., Wang, S. L., Chen, X, “The role of continuous glucose monitoring in physical activity and nutrition management: perspectives on present and possible uses,” Phys Act Nutr, vol. 27, pp. 44-51, Sep 2023.

[3] Ruth S Weinstock, Bergenstal, R. M, Grazia Aleppo, Timothy Bailey, “The Role of Blood Glucose Monitoring in Diabetes Management,” ADA Clinical Compendia, vol. 2020, Oct 2020.

[4] Inzucchi, S. E., Bergenstal, R. M, “Management of Hyperglycemia in Type 2 Diabetes: A Patient-Centered Approach,” Diabetes Care, vol. 35, pp. 1364-1379, June 2012.

[5] Giacomo Cappon, Martina Vettoretti, Giovanni Sparacino, Andrea Facchinetti, “Continuous Glucose Monitoring Sensors for Diabetes Management A Review of Technologies and Applications,” Diabetes Metab Journal, vol. 43, pp. 383–397, Aug 2019.

[6] Pejman Mohammadi, A. Mohammadi, Simsek Demir, Ali Kara, “Compact Size, and Highly Sensitive, Microwave Sensor for Non-Invasive Measurement of Blood Glucose Level” IEEE Sensors Journal, vol. 21, pp. 16033-16042, July 2021.

[7] Asha Ghodake, Balaji Hogade, “Wearable Textile Antenna for Glucose Level Monitoring,” International Journal of Electronics and Telecommunications, vol. 69, pp. 219-224, May 2023.

[8] Asha Ghodake, Balaji Hogade, “M Band 2.4 GHz Wearable Textile Antenna for Glucose Level Monitoring,” International Journal of Electrical and Electronics Research, vol. 11, pp. 39-43, Feb 2023.

[9] Saha, S., Cano-Garcia, H., Sotiriou, I. et al, “A Glucose Sensing System Based on Transmission Measurements at Millimetre Waves using Micro strip Patch Antennas,” Scientific Reports, vol. 7, July 2017.

[10] Yaqub Mahnashi; Khurram Karim Qureshi; Abdullah A. Al-Shehri; Hussein Attia, “Design and Experimental Validation of a Noninvasive Glucose Monitoring System Using RF Antenna-Based Biosensor,” IEEE Sensors Journal, vol. 23, pp. 2856 – 2864, Dec 2021.

[11] Abhishek Kandwal, Louis W. Y. Liu, Jingzhen Li, Yuhang Liu, Huajie Tang, et.al, “Designing Highly Sensitive Microwave Antenna Sensor with Novel Model for Noninvasive Glucose Measurements,” Progress In Electromagnetics Research, vol. 176, pp. 129-141, Jan 2023.

[12] C. Hertleer, H. Rogier, L. Vallozzi, L. Van Langenhove, “A textile antenna for off-body communication integrated into protective clothing for firefighters,” IEEE Trans—Antennas Propagation, vol. 57, pp. 919–925, April 2009.

[13] S. Dhupkariya, V. K. Singh, A. Shukla, “A Review of Textile Materials for Wearable Antenna,” Journal of Microwave Engineering & Technologies, vol. 1, pp. 07-14, Feb 2014.

[14] Asha Pandit Ghodake, B.G. Hogade, “2.4 GHz Compact Textile Antenna for Body Wear Application and Monitoring of Health Parameters,” International Journal of Sensors, Wireless Communications and Control, vol. 13, pp. 326-338, Oct 2023.

[15] S. B. Roshni, M. P. Jayakrishnan, P. Mohanan, K. P. Surendran, “Design and fabrication of an E-shaped wearable textile antenna on PVB coated hydrophobic polyester fabric,” Smart Materials and Structures, vol. 26, Sept 2017.

[16] Asha Pandit Ghodake, B.G. Hogade, “2.4 GHz Wearable Cotton Antenna as Temperature Sensor,” International Journal of COMADEM, vol. 26, March 2023.

[17] R. Sreelakshmy, S. Ashok Kumar, T. Shanmuganantham, “A wearable type embroidered logo antenna at ISM band for military applications,” Microwave and Optical Technology Letters, vol. 59, pp. 2159–2163, Aug 2017.

[18] Bashyam Sugumaran, Ramachandran Balasubramanian, Sandeep Kumar Palaniswamy, “Reduced specific absorption rate compact flexible monopole antenna system for smart wearable wireless communications,” International Journal of Engineering Science and Technology, vol. 24, pp. 682-693, June 2021.

[19] M. Fernandez, H. G. Espinosa, D. V. Thiel, A. Arrinda, “Wearable slot antenna at 2.45 GHz for off‐body radiation: Analysis of efficiency, frequency shift, and body absorption,” Bio Electro Magnetics, vol. 39, pp. 25-34, Sept 2017.

[20] Asha Pandit Ghodake, B.G. Hogade, “SAR, Sweat and Bending Analysis for the ISM Band Wearable Jeans Antenna,” International Journal of Microwave and Optical Technology, vol. 18, pp. 14-22, Dec 2022.

[21] Rahul B. Khadase, Anil Nandgaonkar, Brijesh Iyer, Abhay Wagh, “Multilayered Implantable Antenna Biosensor for Continuous Glucose Monitoring: Design and Analysis,” Progress In Electromagnetics Research C, vol. 114, pp. 173–184, Aug 2021.

[22] Chaouki Hannachi, Frederique Deshours, George Alquie, Hamid Kokabi, “Assessment of Finger Fat Pad Effect on CSRR-Based Sensor Scattering Parameters for Non-Invasive Blood Glucose Level Detection,” Sensors, vol. 23, pp. 473, Jan 2023.