Basic Study on Measurement of Return Loss and Smith Chart Change Using Microstrip Patch Antenna with Concentration Transition for Non-invasive Blood Glucose Measurement

Rae-Hyun Yu1 · Seung-Yeop Rhee2 · Kyung-Ho Kim1

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Abstract
This paper describes a basic study on the measurement of return loss and change in Smith chart using a microstrip patch antenna (MPA) with concentration transition to perform non-invasive blood glucose measurements. To evaluate blood glucose level changes in the human body, the concentration of measurements was changed 10 times to an equivalent of 100 mg/dL in a range of 0–1000 mg/dL to reflect a concentration of 400 mg/dL, which is the fatal level of diabetes. Five types of MPAs were fabricated that formed resonant frequencies in the 1, 2, 3, 4, and 5 GHz bands, and were used in the experiment. Each MPA constituted a sharp narrow band characteristic and induced a large change in return loss. By measuring the return loss and Smith chart to evaluate the concentration change at resonant frequencies, the return loss was observed to change by an average of 0.058 dB for every 100 mg/dL change, and the impedance magnitudes and phase angles analyzed through the Smith chart were observed to have a certain tendency, which confirmed that they were changed. This study shows that for performing non-invasive measurements of blood sugar level, measuring the change in return loss can provide a more stable and reliable measurement compared to the two methods that are simultaneously used to view the samples.

Keywords Non-invasive measurement · Blood glucose · Microstrip patch antenna · Reflection · Smith chart

1 Introduction

According to the International Diabetes Federation, there were an estimated 400 million diabetics in 2019 and there will be an estimated 700 million in 2045 [1]. This is a high figure and indicates an increase of 51%; thus, new methods are required to reduce it. In fact, diseases caused by unstable blood glucose levels are more likely to result in serious complications, which can lead to fatal conditions such as heart attacks or strokes [2]. Moreover, diabetics face an increased risk of complications from COVID-19. If exposed to COVID-19, they face a very high probability of complications owing to large changes in blood glucose levels [3]. Diabetics that are seriously affected by blood glucose level changes and those who require blood glucose level management must often check their blood glucose level. The most commonly used method is by drawing blood directly through a needle and measuring the blood glucose level. However, this method is inconvenient and painful, and poses a risk of secondary infection [5]. Additionally, there is a constant consumption cost of using disposable needles owing to the frequent blood glucose level measurements that must be performed several times a day, resulting in an additional burden for the patient.

Various non-invasive blood glucose level measurement methods have been proposed to address this problem, such as via infrared spectroscopy [6] or Raman analysis [7]. These methods aim to non-invasively measure blood glucose concentration, and perform measurements through any medium. However, the interference with light coming from the outside significantly influences the measurements, and a small
influence also occurs during production, which makes these methods difficult to commercialize. However, microwaves exist in sources that pass through the medium and they are not significantly affected by light [8]. They can penetrate deeper than light, thereby making them more suitable for measuring blood sugar concentration. A method of measuring blood glucose concentration by emitting microwaves has been proposed, which measures the change in the dielectric constant when concentration changes occur [9]. A certain tendency is observed when the blood glucose concentration changes; however, it is measured using two ports and the change width is small, making it difficult to obtain accurate measurements [10].

The human body comprises various substances, such as blood and plasma. Generally, changes in glucose levels in the plasma are used to identify changes in blood glucose levels [11]. In the general population without special diseases, the glucose level varies from 50 to 150 mg/dL, and in diabetic patients, it can go up to 400 mg/dL [12].

Some studies have focused on identifying the change in the dielectric constant according to glucose concentration by frequency band by using purified water or a microstrip patch antenna (MPA) [13, 14].

To address the challenges of current methods, this study proposes radiating microwaves used in previous studies into an MPA to measure the glucose concentration via changes in return loss values and Smith charts. We fabricated MPAs with resonant frequencies of five bands and sharp return loss curves to conduct experiments. The Smith chart can confirm the impedance magnitude and phase angle, and simultaneously compare them with the return loss value. The concentration changes were divided into 100 mg/dL levels in a range of 0–1000 mg/dL such that they had a resolution of up to 400 mg/dL, as suggested above, and the experiment was conducted using these 10 concentration changes.

2 Microstrip Patch Antenna

Although the MPA enabled the measurement of blood glucose concentration using devices, it employs the gigahertz band that is harmful to the human body [15]. Additionally, research has been conducted at 2 GHz; therefore, in this study, MPAs with resonant frequencies of 1, 2, 3, 4, and 5 GHz were fabricated. The sharp return loss graphs induced dramatic changes in return loss values owing to changes in concentration rather than communication.

2.1 MPA Design

The MPA was designed via simulations performed using the CST program. A 3.2 mm thick FR-4 dielectric ($\varepsilon = 4.3$) was used to fabricate the MPAs, which also employed the coaxial probe feeding method.

Figure 1 shows the front view of the designed MPA. The patch is situated in the middle with a certain ratio. The back side is covered with copper for grounding, and a hole is provided for feeding the coaxial probe. The dimensions of the antennas manufactured for each resonant frequency are listed in Table 1.

The S-parameter (magnitude in dB) simulation results of the MPA with 3 GHz resonance frequency are shown in Fig. 2.

The S-parameters of the MPAs with resonant frequencies of 1, 2, 4 and 5 GHz also showed a similar sharp graph. Additionally, the return loss values of all resonant frequencies were under −10 dB.

2.2 MPA Test

Prior to the experiment, the characteristics of the fabricated MPAs were identified. A network analyzer (E8364A) was used to measure their return loss values and the MPA was placed in a radio frequency diagnostic chamber for testing and measurements.
From Fig. 3, it can be observed that the fabricated MPA has narrowband characteristics, similar to the simulations. Figure 4 shows the return loss values of the MPA with resonant frequency of 3 GHz during simulation and test, wherein the center frequency shift based on the frequency shift is 0.1984, and the return loss is under $-10$ dB. Figure 2 shows the ideal graph of the MPA obtained using the S-parameter program, and Fig. 3 shows the fabricated MPA. The ideal MPA ignores environmental factors; hence, there is a slight difference between values of the ideal and fabricated MPAs.

The resonant frequency return loss measurement for each band MPA produced as a value for Table 1 is equal to Table 2. The mean loss is $-29.180$ dB, and the mean change in the center frequency according to frequency shift is approximately $0.1535$ GHz. All return loss values in each band were under $-10$ dB, and they were verified to be available during the experiment.

### 3 Methods

This study aims to research non-invasive blood glucose level measurement methods to detect changes in blood glucose concentration. The actual experiment was not conducted on humans, but on purified water with glucose concentration adjusted to the amount of blood glucose level in the human body.

#### 3.1 Glucose Concentration Control of Purified Water

The general level of blood glucose change in humans varies from 100 to $\pm 50$ mg/dL, and in diabetic patients to 400 mg/dL. Based on this, a sample measurement was constructed by constantly changing the glucose concentration in purified water during the experiment.

Purified water was based on 1 dL, and glucose was administered 10 times in 100 mg increments. This translates to a concentration change of approximately 0.1% after each administration, and the total concentration was changed from 0% to approximately 1%.
3.2 Experimental Conditions

The experiment aimed to measure the return loss and Smith chart values. A network analyzer (E8364A) was used for confirmation, and after placing the MPA in the RF diagnostic chamber shown in Fig. 5, the measurement object was placed on the front part of the patch. The temperature of the chamber was maintained at room temperature (approximately 28 °C) [16]. Additionally, the inside and outside parts of the chamber were disconnected to eliminate factors that could interfere with the glucose concentration measurements.

Figure 6 shows that the MPA with the resonance frequency of 3 GHz is placed vertically. The MPA is fixed 20 cm from the bottom of the RF diagnostic chamber, and the measurement object is placed on it.

A plastic material was used for the container holding the measurement object and the support used to fix the measurement structure. The size of the container was 150 × 150 × 25 mm (width × length × height) and that of the fixing base was 180 × 160 × 2000 mm.

4 Measurement Results

The return loss and Smith chart changes based on the concentration changes in the measurement object were measured for MPAs with resonant frequencies of 1, 2, 3, 4, and 5 GHz. The S11 (1 Port) method was used for measurements.

4.1 Return Loss Results

Figure 7 shows the return loss of the MPA with 3 GHz resonance frequency for the object with a concentration of 0% (0 mg/dL). It can be confirmed that a frequency shift is generated when the container containing the measurement object is placed in the front portion of the patch. Under normal conditions, the return loss was −32.133 dB under 3.1984 GHz, and it was confirmed that it changed to −11.138 dB under 3.5550 GHz.

Figure 8 shows the return loss of the MPA with 3 GHz resonance frequency for the object with a concentration of 1% (1000 mg/dL). Compared to the value obtained for the object with 0% concentration, the value changed from −11.138 dB to −10.774 dB under 3.5550 GHz. Thus, a change of 0.364 dB was detected.

Figure 9 shows the return loss values of the MPAs with 1, 2, 4, and 5 GHz resonance frequencies for the object with 0% concentration.

Figure 10 shows the return losses of the MPAs with 1, 2, 4, and 5 GHz resonance frequencies for the object with 1% concentration.

Table 3 shows the return loss values measured at the resonant frequency of the various MPAs.
The average return loss values for every 100 mg/dL change in glucose concentration for MPAs of each frequency are listed in Table 4. The amount of change can be observed to increase from low to high frequency. The total average return loss change was 0.058 dB.

The standard deviations of return loss value for every 100 mg/dL change in glucose concentration for each frequency are also listed in Table 4. The standard deviation value rapidly increases 3 GHz onwards, and that for 5 GHz is approximately 2.9 times higher than that for 1 GHz.

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4.2 Smith Chart Results

Figure 11 shows the Smith chart of the MPA with 3 GHz resonance frequency for the object with 0% (0 mg/dL) concentration. The 3.555 GHz-based resistance is 41.879 Ω and 1.1230 nH reactance is 25.083 Ω.

Figure 12 shows the Smith chart of the MPA with 3 GHz resonance frequency for the object with 1% (1000 mg/dL) concentration. The 3.555 GHz reference resistance is 40.998 Ω and 1.1584 nH reactance is 25.875 Ω.

4.3 Impedance Magnitude Results

The resistance and reactance (capacitance or inductance) were extracted using the Smith charts and the impedance magnitude was calculated as follows:

\[ Z = \sqrt{R^2 + (X_L - X_C)^2} \]  

(1)

Table 5 lists the impedance magnitudes, calculated using Eq. (1), of the MPAs with different frequencies.

| mg/dL | 1 GHz | 2 GHz | 3 GHz | 4 GHz | 5 GHz |
|-------|-------|-------|-------|-------|-------|
| 0     | 57.824| 37.159| 48.816| 66.257| 49.725|
| 100   | 57.768| 37.083| 48.650| 65.745| 46.675|
| 200   | 57.988| 36.762| 48.520| 65.839| 49.596|
| 300   | 58.183| 36.365| 48.392| 65.839| 49.591|
| 400   | 58.218| 36.546| 48.264| 65.746| 49.658|
| 500   | 58.336| 36.429| 48.264| 65.574| 49.681|
| 600   | 57.996| 36.365| 48.264| 65.574| 49.658|
| 700   | 57.948| 36.013| 48.264| 65.816| 49.669|
| 800   | 57.956| 35.683| 48.264| 65.574| 49.681|
| 900   | 57.888| 35.613| 48.264| 65.574| 49.591|

4.4 Phase Angle Results

The resistance and reactance (capacitance or inductance) were extracted using the Smith charts and the phase angles were calculated as follows:

\[ \theta = \tan^{-1}\left(\frac{X_L - X_C}{R}\right) \]  

(2)

Table 6 lists the phase angle results for the MPAs with different resonant frequencies [°].

| mg/dL | 1 GHz | 2 GHz | 3 GHz | 4 GHz | 5 GHz |
|-------|-------|-------|-------|-------|-------|
| 0     | −53.084| −36.139| 30.919| 9.878 | 0.158 |
| 100   | −53.378| −36.325| 31.245| 10.787| 0.228 |
| 200   | −53.552| −36.720| 31.199| 11.245| 0.068 |
| 300   | −53.769| −36.679| 31.287| 11.895| −0.037 |
| 400   | −54.064| −36.857| 31.343| 12.196| 0.057 |
| 500   | −54.220| −36.716| 31.466| 12.650| −0.038 |
| 600   | −54.375| −36.852| 31.573| 12.939| −0.007 |
| 700   | −54.425| −36.827| 31.760| 13.201| −0.013 |
| 800   | −54.489| −36.753| 32.079| 13.496| −0.186 |
| 900   | −54.676| −36.894| 32.240| 13.749| −0.180 |
| 1000  | −54.815| −36.897| 32.257| 13.931| −0.151 |
Table 6 lists the phase angle results, calculated using Eq. (2), for the MPAs with different frequencies.

5 Conclusion

This study involves basic research on a non-invasive blood sugar measurement method, and the goal of the experiment was to detect changes in blood sugar concentration levels in the human body. Five MPAs with frequencies of 1, 2, 3, 4, and 5 GHz were fabricated, and a measurement object to measure the changes in blood sugar concentration levels in the human body was fabricated to measure return loss changes and construct the Smith charts.

By dividing 0–1000 mg/dL concentration changes into 100 mg/dL units and experimenting with concentration changes over 10 steps, the tendency of constant increase in return loss was confirmed. It was also confirmed that the increase tended to be higher at higher frequencies. Additionally, the change in impedance magnitude was measured using Smith charts, and it was confirmed to decrease in the MPAs with 2, 3, and 4 GHz frequencies. By calculating and checking the phase angle, the tendency to increase or decrease was confirmed to be more consistent than that in the impedance magnitude. In summary, this study showed that blood glucose concentration changes in the human body can be measured by analyzing the return loss and Smith chart in higher resonant frequency bands.

Based on the results of this study, in the future, we will measure blood glucose changes in human participants by performing an in-depth analysis of return loss values and Smith charts.

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Rae-Hyun Yu received BS in Electronic and Electrical Engineering, from Dankook University (2020). He is currently M.Eng.-Ph.D. course student in Control and Signal Processing Engineering, Dankook University.
Seung-Yeop Rhee received Ph.D. degree in electrical engineering from Yonsei university. He is currently a professor at Chonnam University. His research interests are analysis/design of electromagnetic structures, antenna and RF circuits.

Kyung-Ho Kim received M.S. and Ph.D. degrees in biomedical engineering from Keio University, Japan. He worked at in SAIT (Samsung Advanced Institute of Technology) from 2000 to 2006. He is currently a professor at Dankook University. His research interests are measurements & signal Processing, sensor system and its applications.