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Investigation of Resonant Frequency and Impedance for Noninvasive Blood Glucose Monitoring

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***Abstract*—Noninvasive blood glucose monitoring (NBGM) provides a prospective approach for patients with diabetes with the advantages of no pain and continuous monitoring. In order to better understand the influence of blood glucose in NBGM, in this paper, the blood mimicking phantoms with different amounts of glucose content were fabricated. Furthermore, the resonant frequency was measured by the vector network analyzer (VNA) when the blood mimicking phantom was attached on the spiral microstrip resonator. In addition, the impedance of blood mimicking phantom was acquired by the impedance analyzer in the frequency range 10 KHz to 1000 KHz when a patch resonator was adopted. The results showed that as the amount of glucose content increased, the resonant frequency increased linearly. However, the change of impedance was nonlinear. The relationship between impedance and the amount of glucose content could be fitted by the quadratic polynomial.**

Keywords—resonant frequency; impedance; measurement; blood mimicking phantom; Noninvasive blood glucose monitoring

I. Introduction

Diabetes, which is caused by the poor functioning of the pancreas, is one of the most commonly seen metabolic diseases[1]. It is estimated that there are 415 million people with diabetes all over the world in 2015. More seriously, the amount of people with diabetes will be up to 642 million in 2040[2]. Diabetes may cause serious complications, including kidney failure, diabetic retinopathy, and diabetic foot. Thus, diabetes has a great impact on patients' health[3]. However, until now, due to the complications of diabetes, the diabetes can only be managed with frequent monitoring of blood glucose levels[4]. Therefore, an approach which can achieve the blood glucose monitoring noninvasively and continuously is important and necessarily.

Generally, the approaches of blood glucose monitoring can be divided into invasive, micro-invasive and noninvasive monitoring[5, 6]. Compared with invasive and micro-invasive monitoring, noninvasive blood glucose monitoring (NBGM) has the advantages of no pain, comfort and low cost[7]. Furthermore, it is readily monitored the blood glucose levels continuously [8]. Thus, NBGM is one of the most attractive approaches for patients with diabetes[9].

According to the techniques employed, the NBGM can usually be categorized as optical monitoring, radio frequency (RF) techniques, reverse iontophoresis, and so on[10]. Thus far, many researchers have demonstrated the optical techniques using in blood glucose monitoring [11-14]. In addition, a limited number of investigations have been published employing RF techniques for sensing changes of blood glucose. Specifically, the phases of resonant frequency were acquired when the glucose aqueous solutions, of which the concentrations were from 30 mg/dL to 300 mg/dL, were adopted in[15]. In [16], the changes of resonant frequency were investigated by using the glucose aqueous solution and pig blood, respectively in the glucose concentration range 100mg/dL to 600 mg/dL. Similarly, a microwave resonator was presented in [17], and the resonant frequencies of glucose aqueous solution and human blood with different glucose concentrations were studies, respectively. In[18], the effects of stirring and temperature variation on the impedance were investigated when the glucose aqueous solutions were utilized. Additionally, the impedance difference between glucose aqueous solution and human blood was acquired in the frequency range 0.1Hz to 10MHz in[19]. However, in terms of dielectric properties, there is a little difference between glucose aqueous solution and realistic blood owing to the complications of blood components. In addition, it may cause the waste when the realistic blood is used as the experimental subject. Furthermore, these aforementioned investigations were only concentrated on the influence of glucose content on resonant frequency or impedance. However, resonant frequency or impedance, which is more appropriate for NBGM, is still ambiguous. Therefore, a comparison between resonant frequency and impedance for sensing changes of blood glucose is important and necessary.

In this work, we aim to study the influences of blood glucose content on resonant frequency and impedance, respectively. For this purpose, the blood mimicking phantoms with different amounts of glucose content are fabricated. The remainder of this paper is organized as follows. In Section II, we will present the fabrication of blood mimicking phantom and the measurements of resonant frequency and impedance.

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Section III is about the experimental results and fitting. The final section is the conclusion.

II. Experimental Setup

A. Fabrication of Blood Mimicking Phantoms

The ingredients of blood mimicking phantom include de-ionized water, detergent, gelatin, edible oil, and sodium chloride. Table I lists the amounts of different ingredients. Fig.1 shows the sample of blood mimicking phantom. Specifically, the fabrication of blood mimicking phantom requires the following steps:

1) mix 120g gelatin and 350g de-ionized water in a beaker, and cover the beaker with plastic film;

2) heat the mixture up to 75 Centigrade, and the heating time is about 20 minutes;

3) leave the mixture to cool until the room temperature, and add 455g de-ionized water and 4.2g sodium chloride into the mixture;

5) add 140g detergent into the mixture;

6) add 52.5g edible oil into the mixture whilst stirring the mixture slowly;

7) pour the mixture into five containers. The container is circular, and the diameter and height is 64mm and 14mm, respectively;

8) add 0.4g, 0.8g, 1.2g, 1.6g, 2.0g glucose into the containers, respectively, and stirring the mixtures slowly;

9) leave the mixtures to solidify. The height of each mixture is 10mm.

TABLE I INGREDIENTS OF BLOOD MIMICKING PHANTOM

Ingredient	Amount
de-ionized water	805g
detergent	140g
gelatin	120g
edible oil	52.5g
sodium chloride	4.2g

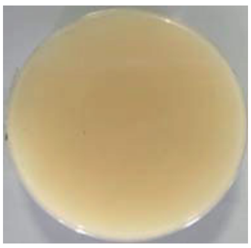

Fig.1 Blood mimicking phantom.

B. Measurement of Resonant Frequency

In this paper, the blood mimicking phantoms with different amounts of glucose content were cut into the cuboids. The dimension of each cuboid was approximately 43mm (length) × 22mm (width) × 10mm (height). As demonstrated in Fig.2, in order to obtain the resonant frequencies of different blood mimicking phantoms, a vector network analyzer (VNA) and a spiral microstrip resonator were utilized. The blood mimicking phantom was placed on the surface of spiral microstrip resonator, and the S11 parameter was measured by the VNA in the frequency range 670MHz to 770MHz.

(a) (b)

Fig.2 (a) Measurement of resonant frequency; (b) spiral microstrip resonator.

C. Measurement of Impedance

As shown in Fig.3, the impedances of blood mimicking phantoms with different amounts of glucose content were measured via the impedance analyzer and patch resonator when the frequency was from 10 KHz to 1000 KHz. In this work, the blood mimicking phantom was fastened with bandages to ensure that the phantom was in close contact with the patch resonator.

(a) (b)

Fig.3 (a) Measurement of impedance; (b) patch resonator.

III. Result and Analyses

A. Dielectric Properties of Blood Mimicking Phantom

Fig.4 illustrates the relative permittivity of blood mimicking phantom without glucose when the frequency was below 750MHz. It is worth noting that the relative permittivity of realistic blood is acquired from[20]. From Fig.4, it could be observed that as the frequency increased, the relative permittivity of phantom decreased. For instance, the relative permittivity was about 95 at 10MHz, whereas the value was less than 75 at 750MHz. On the other hand, the results showed that the relative permittivity between blood mimicking phantom and realistic blood was almost the same when the frequency was from 50MHz to 750MHz.

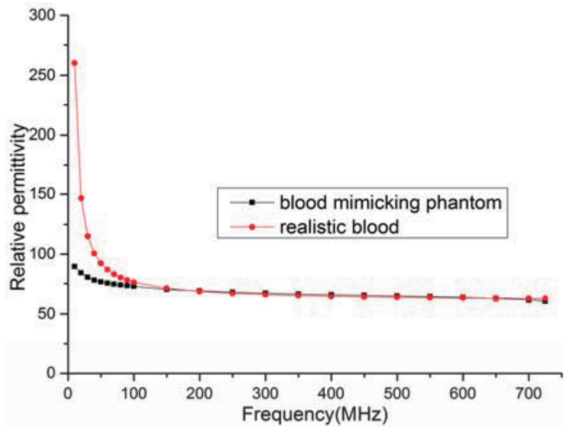

Fig.4 Relative permittivity of blood mimicking phantom and realistic blood.

Fig.5 shows the conductivity of blood mimicking phantom without glucose. The conductivity was 0.9S/m when the frequency was 10MHz. As the frequency increased, the conductivity increased. The conductivity is more than 1.18S/m at 750MHz. In addition, the conductivity gap between blood mimicking phantom and realistic blood was less than 0.3S/m in the whole band.

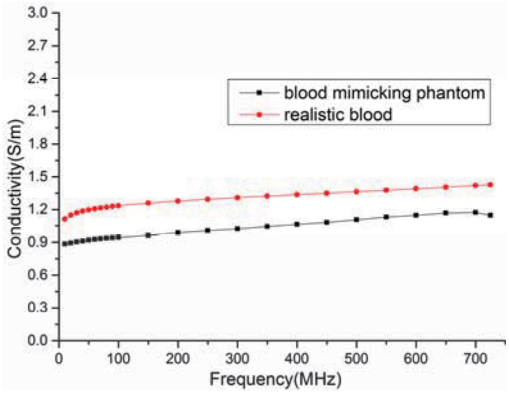

Fig.5 Conductivity of blood mimicking phantom and realistic blood.

B. *Resonant Frequencies of Phantoms with Different Amounts of Glucose Content*

The S11 parameters of blood mimicking phantoms with different amounts of glucose content are shown in Fig.6. The resonant frequency of each phantom was identified as being the frequency of the notch in S11 parameter. It was interesting to observe that as the amount of glucose content increased, the resonant frequency moved from left to right. The resonant frequencies were 713.1MHz, 717.8MHz, 721.5MHz, 722.5MHz, and 726.2MHz, respectively, when the amounts of glucose content were 0.4g, 0.8g, 1.2g, 1.6g, and 2.0g.

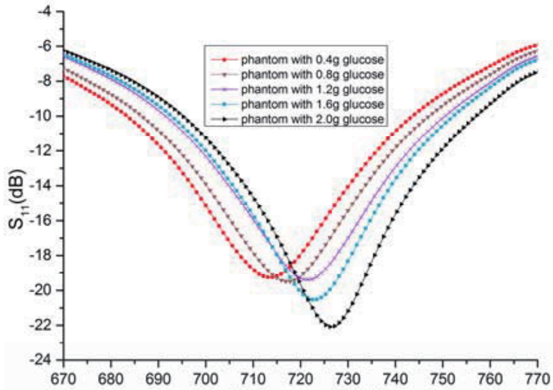

Fig.6 S11 of blood mimicking phantoms with different amounts of glucose content.

Fig.7 demonstrates the curve fitting between the amount of glucose content and resonant frequency. As shown in (1), it could be represented by linear fitting. The slope of fitting was 7.737, and the intercept was 71.094.

$$y = 7.737 \cdot x + 710.94 \qquad (1)$$

where y is the resonant frequency, and x is the amount of glucose content.

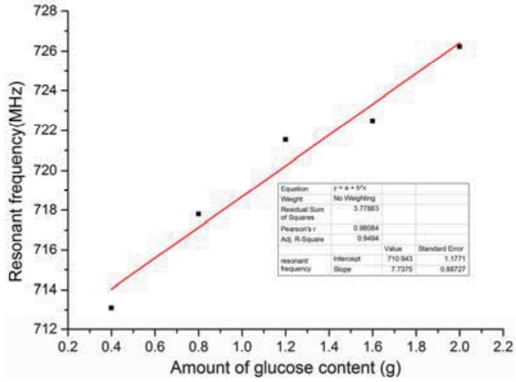

Fig.7 Fitting of resonant frequency and amount of glucose content.

C. *Impedances of Phantoms with Different Amounts of Glucose Content*

The impedances of blood mimicking phantoms with different amounts of glucose content are plotted in Fig.8. As the frequency increased, the impedance of phantom with 0.4g glucose decreased rapidly. The impedance almost remained the same when the frequency was over 200 KHz. Other phantoms also showed similar variation. On the other hand, as the amount of glucose content increased, the impedance increased. However, the change of impedance was nonlinear. Specifically, the impedances were 111.63Ω, 111.78Ω, 111.94Ω when the amounts of glucose content were 0.4g, 0.8g, and 1.2g. However, the impedances were about 116.98Ω and 121.16Ω when the amounts of glucose content were 1.6g and 2.0g.

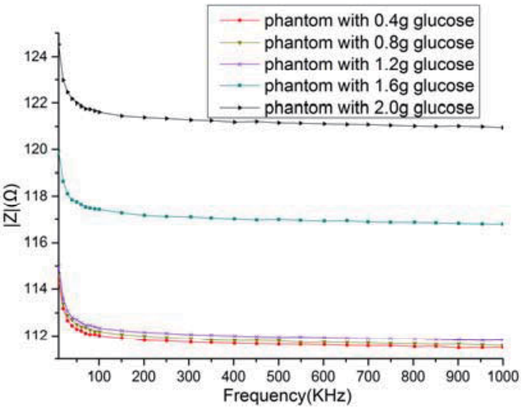

Fig.8 Impedances of blood mimicking phantoms with different amounts of glucose content.

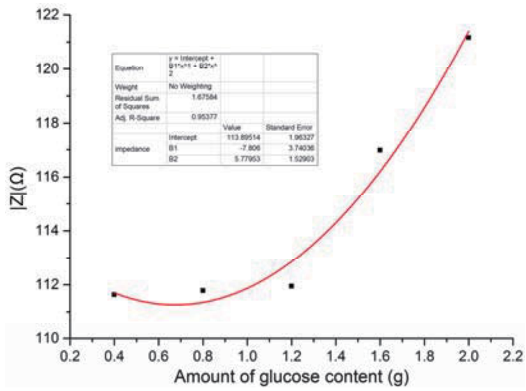

Fig.9 Fitting of impedance and amount of glucose content at 500 KHz.

As shown in Fig.9, in order to understand the influence of glucose on impedance, the fitting between the amount of glucose content and impedance was studied when the frequency was 500 KHz. The fitting result of quadratic polynomial was shown in (2).

$$y = 5.78 \cdot x^2 - 7.81 \cdot x + 113.89 \quad (2)$$

where y is the impedance, and x is the amount of glucose content.

IV. Conclusion

This paper presented the influences of the amount of glucose content on resonant frequency and impedance by using the blood mimicking phantoms for NBGM. The results showed that the resonant frequencies were 713.1MHz, 717.8MHz, 721.5MHz, 722.5MHz, and 726.2MHz, respectively, when the amounts of glucose content were 0.4g, 0.8g, 1.2g, 1.6g, and 2.0g. Thus, it was indicated that as the amount of glucose content increased, the resonant frequency increased linearly. On the other hand, the impedances were 111.63Ω, 111.78Ω, 111.94Ω, 116.98Ω, and 121.16Ω in aforementioned amount of glucose content. The change of impedance could be fitted by quadratic polynomial. Therefore, resonant frequency might be more appropriate for sensing changes of blood glucose in NBGM owing to the linear change of resonant frequency. In the near future, in order to better understand the influences of glucose content on resonant frequency and impedance, we will view the resonant frequency and impedance as the data to train an accurate network model with deep learning methods.

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