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Technical note

Dielectric characterization of water glucose solutions using a transmission/reflection line method

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ABSTRACT

Diabetes mellitus (DM) is a disease that affects millions of people worldwide. In order to be managed, it requires the individuals to measure their blood glucose level in an uncomfortable way several times every day. Thereby, a reliable non-invasive, non-painful blood glucose monitoring system is desirable. Microwave technology has been regarded previously to develop such a sensor by dielectric means, but no clear dielectric characterization of blood glucose dielectric behavior has been hitherto shown. In this paper, a novel study of the effect on the dielectric behavior of water when glucose is added is presented, as a simplified case of blood glucose dielectric behavior. Different water glucose solutions have been dielectrically characterized using a transmission/reflection line method and the effect of the changes of the glucose level in the dielectric behavior has been discussed. Conclusions concerning the development of a non-invasive blood glucose sensor are offered and their validity is discussed.

1. Introduction

Diabetes mellitus (DM) is a well-known disease that affects millions of people worldwide. In 2014 the global prevalence of DM was estimated to be 9% among the adult population (more than 18 years old), meanwhile in 2012 1.5 million deaths were directly caused by it [1]. The same estimations predict that DM will be the seventh leading cause of death in 2030. It consists on the wrong regulation of the hormone insulin by the body. This hormone breaks down the glucose, a kind of sugar that is used as a power source by the body. To have a healthy life, the sugar levels must not fall out of a specific range, because when they do some organs suffer hazardous damage. The most common symptoms of diabetes are poor blood circulation, blurred vision, loss of energy and slow-healing wounds, as well as issuing a volume of urine higher than expected (polyuria) and a strong need of drinking big amounts of water (polydipsia) in order to get rid of the excess of glucose [2].

If the individual does not produce enough insulin, cells cannot get the glucose from blood and its concentration (called glycemia) rises too high (hyperglycemia). Then organic compounds called ketones are produced as a consequence of it [2]. Since ketones are acidic, some organs may result damaged if prolonged exposures to them are produced. On the other hand, if glycemia falls too low (hypoglycemia) there is again not enough glucose to power up the cells and they do not work properly. This condition is strongly dangerous to the body because the brain and the nervous system consume glucose, hence a severe hypoglycemia could lead the diabetic person to a hazardous coma.

Therefore, self monitoring of glycemia levels is fundamental to DM care [3], since it has no known cure but it may be managed with insulin injections. The research on these monitoring devices implies the development of new methods regarding patient-technology interaction [4]. Most daily monitoring is performed with a blood glucose meter, which needs the diabetic person to prick his skin (normally on the fingertip) with a lancet and squeeze it until a drop of blood has been collected on the test strip of the monitor. This is a painful procedure, given that this monitoring may be performed over five times per day. In addition, the lack of accuracy is another drawback of these monitoring methods, often caused by the dirt that may be found in the skin.

Many efforts have been made in order to reduce the discomfort of diabetic people and get a better management of the disease.

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For instance, several autoregressive glucose level prediction models have been studied (e.g. [5], [6]), so that the number of blood measurements may be reduced. A further step was taken with the development of continuous glucose monitoring systems based upon chemical means, which are invasive and make continuous measurements of the blood glucose level of the individual in order to advise the patient when it falls out of the healthy range, or even to automatically manage an insulin injection system (e.g. [7]). However, these systems require the substitution of crucial elements every few days, and they present errors greater than the conventional glucose meters, mainly because of the inflammation effect affecting the skin nearby the sensor [8]. Thus, a non-invasive glycemia monitoring system is desirable. In this regard some attempts have been developed employing several technologies such as optics (e.g. [9]) or even trying to measure the blood glucose level from the individual's breath [10].

Nevertheless, when talking about non-invasive measuring, sensors based on electromagnetic fields or antennas usually take place. Some investigations have been made in this regard, focusing on microwave microstrip resonators as one of the candidate technologies for developing such a device [11–16]. These researches show a certain variation of the relative permittivity of human tissues as well as that of glucose solutions as the glucose level changes. However, they have not had much success so far because this variation does not seem to be clear.

In this paper a measuring method based upon transmission/reflection measures of a coaxial line filled with the liquid under measurement is utilized to present a systematic study of the variation of the relative permittivity of glucose solutions as the glucose level changes, in the range of several GHz. With this method two complex magnitudes are obtained (as explained below) instead of just one of them as it is obtained if a well-known open-ended coaxial probe is used. This advantage allows to enhance the quality of the measurement. Results of different measures are shown and discussion focused on developing a suitable microwave resonator is offered. Our main purpose is the development of a device able to measure the blood glucose level in a non-invasive way. Therefore, a clear dielectric characterization of the effect of glucose in blood is needed in order to make the most suitable design of such a device.

The main component of blood is water, whose dielectric characterization has been recently studied in a very deep manner [17]. Thus, in this paper the study of the effect of glucose in the dielectric behavior of water is presented (as a simplified way to study the effect of glucose in blood). This was done in order to identify the dielectric behavior of water glucose solutions as well as the effect of varying the glucose level, and the most interesting frequency ranges so that a suitable microstrip resonator may be developed in the near future. In addition, although the results shown in this paper are only to be applied to water-glucose solutions and not to blood-glucose solutions, recent studies have shown that the effect of glucose in the dielectric behavior of blood is much greater than those from other components such as maltose, galactose, fructose, ascorbic acid or uric acid [18]. Thus, these results might be very useful even for blood glucose purposes, since glucose seems to be the main contributor to dielectric changes in blood.

The underlying theory of dielectric dispersion characterization is outlined in Section 2, with special focus on the study of the relative permittivity of dielectric materials. Section 3 presents a brief review of the known methods to measure and characterize the relative permittivity, as well as the explanation of the measuring system developed in this work. The results obtained are shown in different ways in Section 4, focusing on the most interesting frequencies observed as well as the dielectric parameters obtained. Finally, in Section 5 the discussion of the results obtained is found, with special emphasis on the future development of a microstrip resonator able to measure the changes in the relative permittivity observed, and in Section 6 the main information provided in this study is summarized.

2. Theory

There are several known physical mechanisms that contribute to the polarization of dielectric media [19]. These phenomena have been fully studied and it has been shown that for biological materials at frequencies ranging $10^8 - 10^{10}$ Hz the most relevant ones are orientation polarization and interfacial polarization.

The orientation polarization takes place in dielectrics comprising permanent dipoles (e.g. water). In the absence of electric field, the thermal motion tends to orient the dipoles at random, while the presence of an electric field makes them rotate to get oriented parallel to it. This is a highly temperature-dependent polarization process. Regarding interfacial polarization, also known as Maxwell-Wagner polarization, it takes place when dielectric particles exist in ionic solutions. In these cases, the motion of the solute ions to follow the electric field applied is stopped by the dielectric particle. Hence, an accumulation of charges at the interfaces between the particle and the ionic solution occurs, and there are oppositely charged interfaces in the particle, which constitute a dipole. Therefore, a suspension of such particles in the solution behaves as a system of induced dipoles. This type of polarization is quite important in the permittivity measurements concerning biological tissues and fluids.

Regardless the kind of polarization induced by an electric field, the electric polarization is always in equilibrium with the field when it is static (i.e. there is no time dependence). When the electric field varies along time this equilibrium may not exist since the motion of the microscopic particles requires some characteristic time to reach a certain value of polarization. If the changes of the time-dependent electric field are faster than the motion of these particles, a phase difference (which depends on the frequency of the field) between the electric field and the electrical displacement must be taken into account. This can be understood only by considering the dielectric permittivity as a complex, frequency-dependent parameter [20]. This way, the frequency-dependent electrical displacement $D(\omega)$ is defined as:

$$D(\omega) = \varepsilon_0 \varepsilon(\omega) E(\omega) \quad (1)$$

where ω is the angular frequency, $E(\omega)$ is the frequency-dependent electric field, ε_0 is the free space permittivity and $\varepsilon(\omega)$ is the frequency-dependent complex relative permittivity, given by:

$$\varepsilon(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega) \quad (2)$$

Hence, even the motion of the microscopic particles is faster enough to follow the variations of the electric field, when it is suddenly switched on it takes a characteristic period of time for the time-dependent polarization $P(t)$ of the dielectric to reach its equilibrium value $P(0)$. Similarly, when the field is suddenly removed the polarization decay caused by thermal motion is described by the relaxation or decay function of the dielectric polarization $\phi(t)$:

$$\phi(t) = P(t)/P(0) \quad (3)$$

It is known that the frequency-dependent complex dielectric permittivity described by Eq. (2) is related to the relaxation function through the Fourier transform [20], and thus the same information may be obtained from both $\varepsilon(\omega)$ and $\phi(t)$. For instance, if the relaxation function obeys the simple exponential law with τ being the characteristic relaxation time of the dielectric:

$$\phi(t) = \exp\left(-t/\tau\right) \quad (4)$$