Non-invasive Glucose Monitoring at mm-Wave Frequencies

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Abstract

In this paper, we review our recent experimental studies to develop a non-invasive blood glucose monitoring system at mm-wave frequencies. A robust 60 GHz radar system is used to differentiate between hemoglobin samples of disparate glucose concentrations through detecting minute changes in their dielectric properties. A new-developed dielectric assessment system (DAK) is used to characterise the electromagnetic properties of the tested samples and identify the amount of change in these parameters at different concentrations of interest.

1. Introduction

Millimeter-wave (mm-wave) frequencies have shown to be promising in developing medical devices for different reasons: enhanced security, reduced interference, available spectrum, and miniaturized sizing for fabricated devices compared to microwave-based ones [1]. Though, there are challenges of using such high frequencies within human-bodies. Among the devices of interest is one that can monitor glucose levels for diabetes. Serious complications would face diabetics who failed to manage their diabetes to meet certain glycemic targets, and hence they are recommended to continually monitor their blood glucose levels and check 2-4 times per day [2]. The leading methodology used to check for blood glucose is through a glucometer device, where a blood sample is taken from the finger-tip and analysed on a strip of test paper. This finger-pricking method is painful, invasive, and costly to the users who must prick their finger multiple times a day to draw blood and constantly purchase a fresh supply of test paper to analyze the samples. To overcome these limitations and discomforts, researchers have conducted thorough investigations over the last decade on alternative, non-invasive methods of blood glucose monitoring. Absorbance spectroscopy techniques [3], such as near infrared and mid infrared spectroscopy, have been widely researched where the scattering of light on biological tissue is used to detect optical signatures of glucose in blood. However, these methods are not only costly to implement but also highly sensitive to changes in physiological parameters such as body temperature and blood pressure, as well as environmental variations in temperature and humidity. External bodily fluids such as breath condensation [4], saliva [5], sweat [6], and tears [7] have been utilized to correlate their glucose content to blood glucose concentrations, but these non-invasive methods are too susceptible to metabolic changes. Despite being quite innovative, these proposed methods either show a low correlation between the measured parameters and blood glucose levels, or the proposed designs are still in their infancy to judge their applicability. In addition to aforementioned efforts, some earlier research works have focused on using radio-frequency (RF) waves to measure the dielectric properties of blood glucose in superficial vessels using split ring resonators [8], microstrip patch antennas [9], vector network analyzers (VNA) [10], and waveguides [11]. All these RF systems have demonstrated success in glucose detection, but they are not immediately viable for at-home use by diabetic patients due to restrictions on these systems that rely on expensive RF tools. This makes the systems impractical for large-scale deployment.

2. Proposed Concept and Experiments

We are proposing a compact low-cost wearable sensing system that utilizes mm-wave radars to non-invasively detect glucose concentration levels for diabetic patients. Towards this goal, we have recently held the following proof-of-concept studies in our labs at Research Institute for Aging (UW-RIA) using a low-cost 60 GHz mm-wave frequency-modulated continuous-wave (FMCW) radar with two-transmitters and four-receivers (2-Tx/4-Rx) to detect changes in dielectric properties of water solutions and blood mimicking material "fake blood" containing different glucose concentrations [12][13].

- Differentiate the amount of sugar in three different drinks (coke, diet coke, and zero coke) using the reflection data from one channel of a 4-port Microwave Network Analyzer (PNA-67GHz) and multi-channel radar.
- Discriminate between various glucose-water concentrations with high accuracy in a 3D printed ear-model, silicone rubber structures, and animal meat slices.
- Investigate the scalability of blood glucose concentrations of different subjects on the reflected data of mm-wave radar.
- VNA analysis on the frequency range (50 – 67 GHz) for clinical blood samples drawn before and after consuming 75mg of glucose while comparing against a reference glucometer device.
- Comparative study for clinical blood samples of two subjects taken pre and post meal while comparing their measurements on a glucometer against a mm-wave radar.
- Differentiate between fake blood samples of assorted glucose concentrations from 0.5 to 3.5 mg/ml in steps of 0.5. A 3D fixture device shown in Fig. 1 was developed to mitigate the placement errors and maintain the position of the sample tube at a short distance from the radar sensor which strikes the samples with periodic electromagnetic waves at very high frequencies. Radar raw data of reflected waves are collected from the four radar channels three times with a very good repeatability. Fig. 2 shows the raw data measured on channel 1 for 0.5, 1.0, 2.0 and 3.0 mg/ml concentrations, while Fig. 3 depicts the averages of the three tests and the corresponding error in each concentration readings.

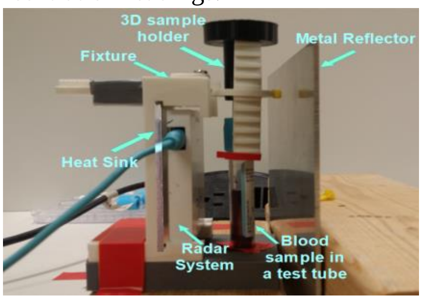

Fig. 1: Radar antennas directed towards sample tube on a 3-D printed fixture.

Preliminary results of these proof-of-concept experiments indicated that mm-waves are suitable for glucose detection through biological mediums at concentrations similar to blood glucose concentrations of diabetic patients. The 60 GHz radar is reliable in detecting changes of glucose levels in blood while monitoring trends among those variations for increasing or decreasing levels. This is demonstrated when radar reflected readings are compared against traditional glucometer measurements and found to follow similar trends but have not that linear scale of the glucose concentrations of the tested samples. We have discussed improving the repeatability and scalability of the integrated system, applying potential user constraints of implementation, and introducing some conventional signal processing (Discrete Time Fourier Transform (DTFT), Power Spectral Density (PSD) and Energy Density Spectrum) and machine learning techniques to identify and distinguish between different glucose concentrations that are found to follow a very clear trend [13]. The issues of identifying samples outside of the training data sets, along with scalability among various people with different physiological features that might impact the radar data are being explored further in our ongoing research. Theoretical modelling of the problem is now being conducted and potential modifications have been identified that may allow for easier scalability and trend identification.

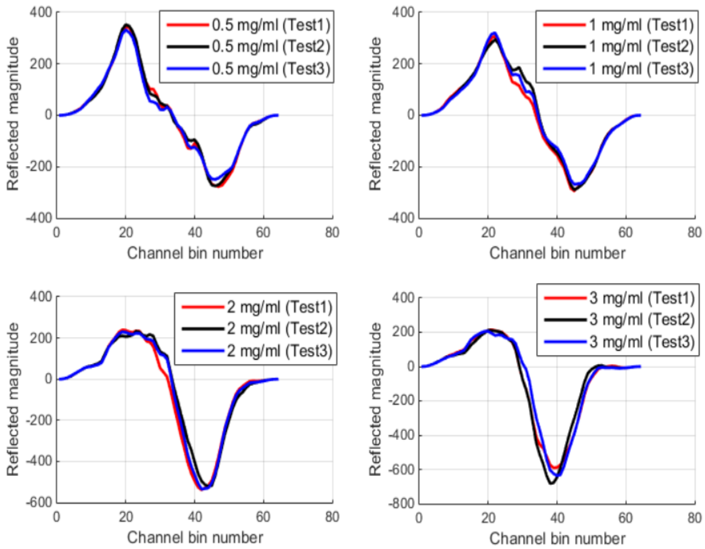

Fig. 2: Raw data measurements on channel 1 for different concentrations

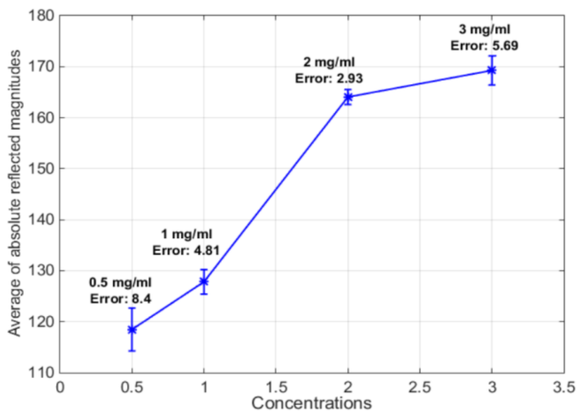

Fig. 3: Averages of magnitudes in three tests and corresponding error.

3. DAK Measurements

The dielectric assessment kit (DAK-TL) system was developed to measure the dielectric properties of thin material layers on the millimeter and sub-millimeter scale and of liquids available in small volumes (0.5 – 50 ml). DAK-TL operates over the frequency range from (5 – 67) GHz. The system is featured with full automation and controlled software; the automated sample platform brings the material under test to the probe and measures the sample thickness with micrometer precision. The applied force can be precisely controlled to enable high measurement repeatability for soft samples such as leather or soft plastic. DAK system would be used for a variety of applications including the characterization of small quantities of liquids (e.g., precious pharmaceutical samples) and the evaluation of small biological samples (e.g., human skin or tumor tissue samples).

In the next study we used the DAK-TL system to measure the electromagnetic properties of the hemoglobin samples that were tested in the test tube arrangement using the mm-wave radar system in Fig. 1. These samples are prepared using a micropipette device in laboratory with disparate glucose content at the following concentrations: 0.5, 1.0, 2.0 and 3.0 mg/ml. The objective is to determine the range of frequencies that are most sensitive to glucose concentration levels and the corresponding change in dielectric parameters at these concentrations. We measure the dielectric constant, conductivity and loss tangent properties of each fake blood sample over the mm-wave range of frequencies (50 – 67 GHz) using the DAK1.2E-TL probe beam. The basic system setup that interconnects the DAK-TL, VNA and PC is shown in Fig. 4. The DAK-TL base system is connected to one port of the VNA via coaxial cable, while connected to the PC via USB. This testing fixture is fully automated and software controlled as we mentioned. The VNA is connected to PC using LAN/Ethernet cable. The liquid sample under test is poured on a metallic petri-dish and placed on the sample platform, which brings it to be in touch with the probe for measurement. Probe has to emerge a distance of 2 – 4 mm inside the liquid to have good contact for stable measurements. DAK system is calibrated using a distilled water at 20C° before starting the liquid measurements.

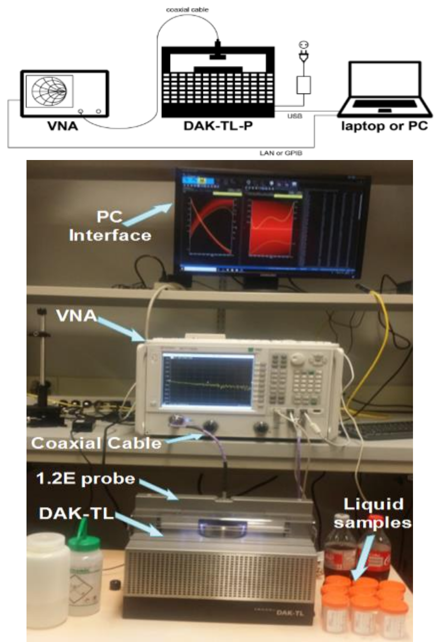

Fig. 4: DAK-TL system setup for dielectric measurements.

Measurements of each blood sample are repeated multiple times and averaged. Fig. 5 compares the relative permittivity for all glucose concentrations over the interested range of frequency that are observed to be decreasing in values as the frequency increases. At 60 GHz frequency for example, the samples of different concentrations are noticed to have very close dielectric constants in the range (10.35 – 11.07). Similarly, Fig. 6 depicts the changes in loss tangent properties for the investigated glucose concentrations over the whole tested spectrum with a trend that increases tenuously with increasing the frequency. In particular, at 60 GHz frequency of interest the loss tangent varies in the range (1.757 – 1.926).

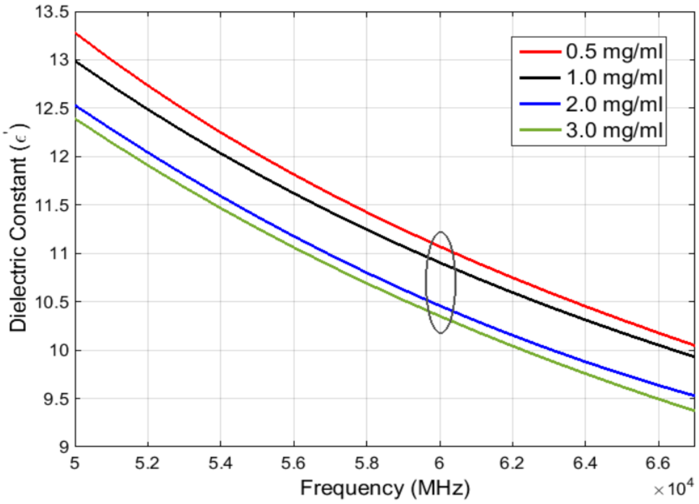

Fig. 5: Relative permittivity measurements for the tested samples.

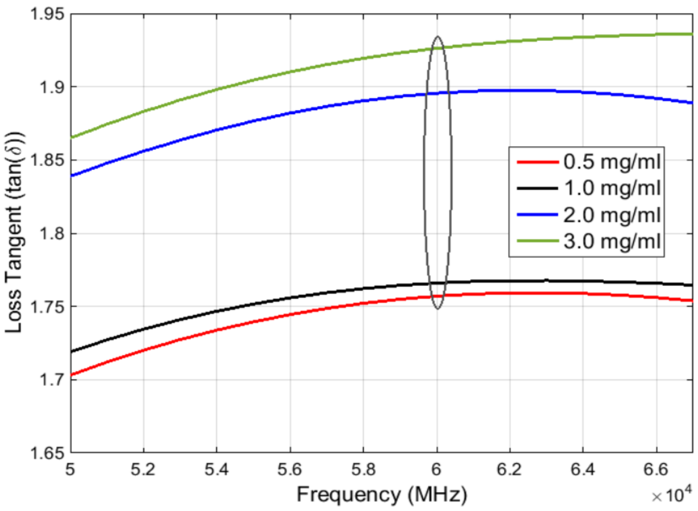

Fig. 6: Loss tangent measurements for the tested samples.

Towards the goal of the front-end design of wearable flexible antennas on the patient's wrist, further investigations are needed to decide upon the sensor type and its mode of operation that could be very sensitive to slight changes in dielectric variations of glucose solutions of similar concentrations to diabetics. Therefore, we aim at measuring the dielectric properties of different water and hemoglobin solutions at similar concentrations to diabetics, from 0.7 – 1.5 mg/ml in steps of 0.1, over the frequency spectrum 200 MHz to 67 GHz. Measured dielectric parameters will be then used to simulate blood sample tubes while experimenting different configurations of TX and RX antennas to observe how the sensor sensitivity could be improved by optimizing the attached antenna positions.

4. Conclusions

In this paper we shortly review our recent experiments that promote a non-invasive blood glucose sensing system. We also demonstrate the capability of detecting slight disparities in concentration levels of glucose contained in hemoglobin samples using a mm-wave radar. The tested samples are characterized using a new-developed dielectric assessment kit system to recognise the amount of change in the dielectric properties of the investigated glucose concentrations. We believe that such promising results could pave the road towards developing a wearable prick-free monitoring device for the diabetics.

Acknowledgement

This work was supported by NSERC CREATE grant, Schlegel-UW Research Institute of Aging (UW-RIA), and by Google's Advanced Technology and Projects group (ATAP).

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